Although the words "he", "him", and "his", are used sparingly in this manual to enhance communication, they are not intended to be gender driven nor to affront or discriminate against anyone reading *Introduction to Marine Gas Turbines*, NAVEDTRA 10094.

PREFACE

This text is written to provide training support for personnel working with gas turbine propulsion systems. It is the first of a series of subject matter directed manuals which will address the field of gas turbine propulsion technology in the U. S. Navy.

Personnel using this material to study for advancement in gas turbine fields should also study texts which will provide the basic foundations of mechanical sciences, such as *Basic Machines,* NAVPERS 10624-A; *Fluid Power,* NAVPERS 16193-B; and at least one conventional rate training manual, such as *Engineman* 3&2, NAVPERS 10541-B.

The text provides a general mechanical and functional description of a marine gas turbine propulsion system, using the LM 2500 turbine installation as an example.

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THE UNITED STATES NAVY

GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

CONTENTS

CREDITS

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Source	Figures
General Electric Co.	5-1, 5-3, 5-4, 5-5, 5-7 5-16, 5-17
Henschel Corp.	5-8

CHAPTER 1

MARINE GAS TURBINE PROPULSION SYSTEMS

This chapter is intended to develop your understanding of the history and development of gas turbines, to familarize you with the basic concepts used by gas turbine designers, and to introduce you to the principal components of gas turbines. You will follow discussions of how the Brayton cycle describes the thermodynamic processes in a gas turbine, how various conditions and design limitations affect gas turbine performance, and how the gas turbine develops and uses hot gases under pressure. You will also learn a large amount of nomenclature related to gas turbines and gas turbine technology.

HISTORY AND BACKGROUND

Until recent years it has not been possible to separate gas turbine technology and jet engine technology. The same people have worked in both fields, and the same sciences have been applied to both types of engines. Recently, the jet engine has been used more exclusively as a part of aviation, and the gas turbine has been used for electric generation, ship propulsion, and even experimental automobile propulsion and some successful racing cars. Even now, many operational turbine power plants use an aircraft jet engine as a gas generator, adding a power turbine and transmission to complete the plant.

In nature, the squid was using jet propulsion long before our science thought of it. There were examples of the reaction principle in early history; however, practical applications of the reaction principle have occurred only recently. This delay is due to slow progress of technical achievement in engineering, fuels, and metallurgy (the science of metals).

Between the first and third centuries A.D., Hero, a scientist in Alexandria, Egypt, described what is considered to be the first "jet engine." Many sources credit him as the inventor. Whether or not this is true, such a device known as the "aeolipile" (fig. 1-1) is mentioned in sources dating back as far as 250 B.C.

Throughout the course of history, there are examples of other well-known scientists using the principle of expanding gases to perform work. Among these were inventions of Leonardo da Vinci (fig. 1-2) and Giovanni Branca (fig. 1-3).

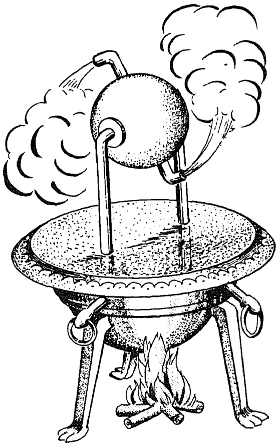

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Figure 1-1.—Hero's aeolipile.

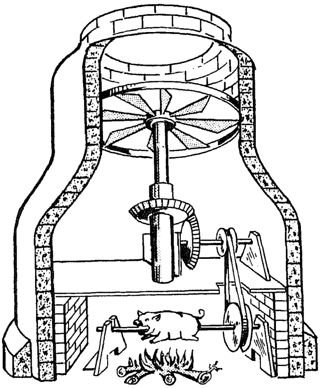

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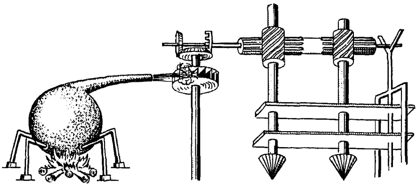
Figure 1-2.—DaVinci's chimney jack.



277.6

Figure 1-3.—Branca's jet turbine.

In the 1680's Sir Isaac Newton described the laws of motion on which are based all devices that use the theory of jet propulsion. Newton's steam wagon is an example of the reaction principle (fig. 1-4).

The first patent for a design that used the thermodynamic cycle of the modern gas turbine, also suggested as a means of jet propulsion, was submitted in 1791 by John Barber, an Englishman.

20TH CENTURY DEVELOPMENT

The patented application for the gas turbine as we know it today was submitted in 1930 by another Englishman, Sir Frank Whittle. His patent was for a jet aircraft engine. Using his own ideas along with the contributions of such scientists as Coley and Moss, Whittle, after several failures, came up with a working gas turbine engine.

You should note that up to this time all of the early pioneers in the gas turbine field were European-born or oriented.

American Development

The United States did not go into the gas turbine field until late in 1941 when General Electric was awarded a contract to build an American version of a foreign-designed aircraft engine. The engine and airframe were both built in one year, and the first jet aircraft was flown in this country in October 1942.

In late 1941 Westinghouse Corp. was awarded a contract to design and build from scratch the first all-American gas turbine engine. Their engineers designed the first axial-flow compressor and annular combustion chamber. Both of these ideas, with minor changes, are the basis for the majority of contemporary engines in use today.

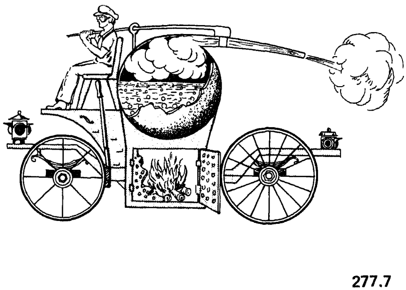


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Figure 1-4.—Newton's steam wagon.

Marine Gas Turbines

The concept of using a gas turbine to propel a ship goes back to 1937 when a Pescara free piston gas engine was used experimentally with a gas turbine. The free piston engine, or "gasifier" (fig. 1-5) is a form of diesel engine, using air cushions instead of a crankshaft to return the pistons. It was an effective producer of pressurized gases, and the German Navy used it in their submarines during World War II as an air compressor. In 1953 the French placed in service two small vessels powered by a free piston engine-gas turbine combination. In 1957 the liberty ship, *WILLIAM PATTERSON*, having six free piston engines driving two turbines, went into service on a transatlantic run.

Over the same period there were a number of applications of the use of a rotary gasifier to drive a main propulsion turbine. The gasifier, or compressor, was usually an aircraft jet engine or turboprop front end. In 1947 the Motor Gun Boat 2009 of the British Navy used a 2,500 hp gas turbine to drive the center of three shafts. In 1951 the tanker *AURIS*, in an experimental application, replaced one of four diesel engines with a 1,200 hp gas turbine. In 1956 the *JOHN SERGEANT* had a remarkably efficient installation which gave a fuel consumption rate of .523 pounds per hp/hr. The efficiency was largely due to use of a regenerator which recovered heat from the exhaust gases.

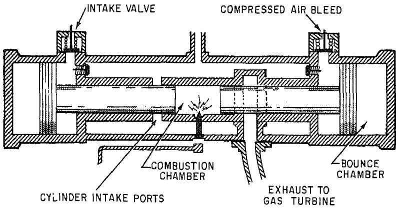

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Figure 1-5.—Free piston engine.

By the late 1950's the gas turbine marine engine was becoming widely used, mostly by European navies. All the applications combined the gas turbine plant with another, conventional, form of propulsion machinery. The gas turbine was used for high-speed operation, and the conventional plant was used for cruising. The most common arrangements were the CODOG (Combined Diesel or Gas) or the CODAG (Combined Diesel and Gas) Systems. Diesel engines give good cruising range and reliability, but they have a disadvantage when used in antisubmarine warfare. Their low-frequency sounds travel great distances through water, making them easily detected by passive sonar. To reduce low frequency sound, steam turbines have been combined in the COSAG (Combined Steam and Gas) configuration, but these require more personnel to operate and do not have the long range of the diesel combinations. Another configuration that has been successful is the COGOG (Combined Gas or Gas). The British County class destroyers use the 4,500 hp Tyne gas turbine engine for cruising and the Rolls Royce Olympus, a 28,000 hp engine, for high speed.

The U.S. Navy entered the marine gas turbine field with the Asheville class patrol gunboats. These ships have the CODOG configuration, with two diesel engines for cruising, and a General Electric LM 1500 gas turbine to operate at high speed. As a result of the increasing reliability and efficiency of new gas turbine designs, the Navy has now designed and is building destroyers and frigates which will be entirely propelled by gas turbine engines.

ADVANTAGES AND DISADVANTAGES

The gas turbine, when compared to other types of engines, offers many advantages. Its greatest asset is its high power to weight ratio. This has made it, in the forms of turboprop or turbojet engine, the preferred engine for aircraft. Compared to the gasoline piston engine, which has the next best power-to-weight characteristics, the gas turbine operates on cheaper and safer fuel. The smoothness of the gas turbine, compared with reciprocating

aircraft, because less vibration reduces strains on the air frame. In a warship, the lack of low-frequency vibration of gas turbines makes them preferable to diesel engines because there is less noise for a submarine to pick up at long range. Modern production techniques have made gas turbines economical in terms of horsepower-per-dollar on initial installation, and their increasing reliability makes them a cost-effective alternative to steam turbine or diesel engine installation. In terms of fuel economy, modern marine gas turbines can compete with diesel engines and may be superior to boiler/steam turbine plants, when these are operating on distillate fuel.

However, there are some disadvantages to gas turbines. Since they are high-performance engines, many parts are under high stress. Improper maintenance and lack of attention to details of procedure will impair engine performance and may ultimately lead to engine failure. A pencil mark on a compressor turbine blade or a fingerprint in the wrong place can cause failure of the part. The turbine takes in large quantities of air which may contain substances or objects that can harm. Most gas turbine propulsion control systems are very complex because several factors have to be controlled, and numerous operating conditions and parameters must be monitored. The control systems must react quickly to turbine operating conditions to avoid casualties to the equipment. Gas turbines produce high-pitched loud noises which can damage the human ear. In shipboard installations special soundproofing is necessary, adding to the complexity of the installation and making access for maintenance more difficult.

From a tactical standpoint, there are two major drawbacks to the gas turbine engine. The first is the large amount of exhaust heat produced by the engines. Most current antiship missiles are heat-seekers, and the infrared signature of a gas turbine makes an easy target. Countermeasures such as exhaust gas cooling and infrared decoys have been developed to reduce this problem.

The second tactical disadvantage is the requirement for depot maintenance and repair repaired in place on the ship and must be removed and replaced by rebuilt engines if anything goes wrong. Here too, design has reduced the problem, and an engine change can be accomplished wherever crane service or a Navy tender is available and the replacement engine can be obtained.

FUTURE TRENDS

As improved materials and designs permit operation at higher combustion temperatures and pressures, gas turbine efficiency will increase. Even now, gas turbine main propulsion plants offer fuel economy and installation costs no greater than diesel engines. Initial costs are lower than equivalent steam plants which burn distillate fuels. Future improvements may make gas turbines the best choice for nonnuclear propulsion of ships up to cruiser size.

At present, marine gas turbines use aircraft jet engines for gas generators. These are slightly modified for use in a marine environment, particularly in respect to corrosion resistance. As marine gas turbines become more widely used, specific designs for ships may evolve. These compressors may be heavier and bulkier than aircraft engines and take advantage of regenerators to permit greater efficiency.

It is unlikely that large gas turbines can be made so simple and rugged that they can be overhauled in place, so they will require technical support from shore. It is possible to airlift replacement engines if necessary, so gas turbine ships can operate and be repaired worldwide on a par with their steam- or diesel-driven counterparts.

The high power-to-weight ratios of gas turbine engines permit the development of high-performance craft such as hydrofoils and surface effect vehicles. Because of their high speed and ability to carry formidable weapons systems, these craft will be seen in increasing numbers in our fleet. In civilian versions, hydrofoils have been serving for many years to transport people on many of the world's waterways. Hovercraft are finding increased employment as carriers of people. They are capable of speeds up to 100 knots, and, if beach

gradients are not too steep, they can reach points inland after crossing seas, marshy terrain, or almost any other level area.

GAS TURBINE OPERATION

A gas turbine engine is composed of three major sections:

1. Compressor(s)
2. Combustion chamber(s)
3. Turbine wheel(s)

A brief description of what takes place in a gas turbine engine during operation follows (see fig. 1-6): Air is taken in through the air inlet duct by the compressor which raises pressure and temperature. The air is then discharged into the combustion chamber(s) where fuel is admitted by the fuel nozzle(s). The fuel-air mixture is ignited by igniter(s) and combustion takes place. Combustion is continuous, and the igniters are deenergized after a brief period of time. The hot and rapidly expanding gases are directed towards the turbine rotor assembly. Kinetic and thermal energy are extracted by the turbine wheel(s). The action of the gases against the turbine blades causes the turbine assembly to rotate. The turbine rotor is connected to the compressor which rotates with the turbine. The exhaust gases then are discharged through the exhaust duct.

Since approximately 75% of the power developed by a gas turbine engine is used to drive the compressor and accessories, only 25% can be used to drive a generator or to propel a ship.

LAWS AND PRINCIPLES

To understand basic engine theory, you must be familiar with the physics concepts used in the operation of a gas turbine engine. In the following paragraphs we have compiled a list of definitions of laws and principles as they apply to the work you will be doing in gas turbines, explained each of them, and then demonstrated how they apply to a gas turbine.

BERNOULLI'S PRINCIPLE: If a fluid flowing through a tube reaches a constriction, or

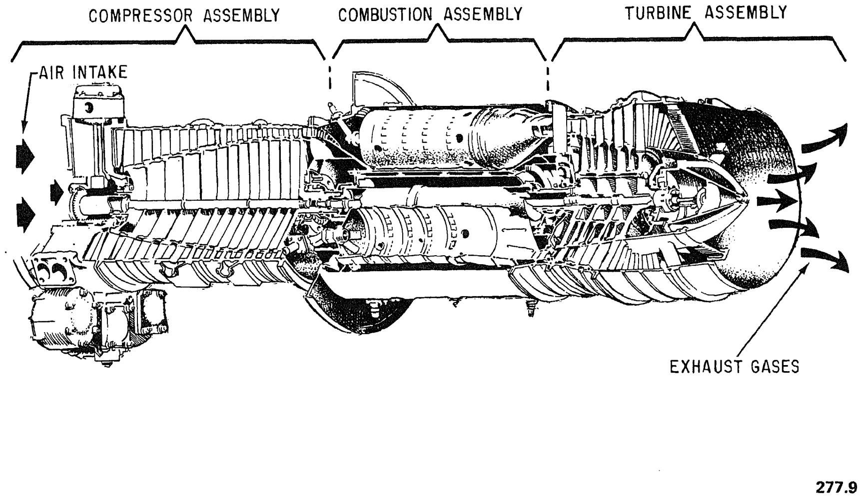

Figure 1-6.—Gas turbine operation.

narrowing of the tube, the velocity of fluid flowing through the constriction increases and the pressure decreases.

BOYLE'S LAW: The volume of an enclosed gas varies inversely with the applied pressure, provided the temperature remains constant.

CHARLES' LAW: If the pressure is constant, the volume of an enclosed dry gas varies directly with the absolute temperature.

NEWTON'S LAW: The first law states that a body at rest tends to remain at rest, and a body in motion tends to remain in motion. The second law states that an unbalance of force on a body tends to produce an acceleration in the direction of the force, and that the acceleration, if any, is directly proportional to the force and inversely proportional to the mass of the body. Newton's third law states that for every action there is an equal and opposite reaction.

PASCAL'S LAW: Pressure exerted at any point upon an enclosed liquid is transmitted undiminished in all directions.

BERNOULLI'S PRINCIPLE

Consider the system illustrated in figure 1-7. Chamber A is under pressure and is connected by a tube to chamber B which is also under pressure. Chamber A is under static pressure of 100 psi. The pressure at some point, point X in this case, along the connecting tube consists of a velocity pressure of 10 psi exerted in a direction parallel to the line of flow, plus the unused static pressure of 90 psi, which obeys Pascal's law and operates equally in all directions. As the fluid enters chamber B from the constricted space, it is slowed down, and, in so doing, its velocity head is changed back to pressure head. The force required to absorb the fluid's inertia equals the force required to start the fluid moving originally, so that the static pressure in chamber B is again equal to that in chamber A although it was lower at intermediate point X.

The illustration (fig. 1-7) disregards friction and is therefore not encountered in actual practice. Force or head is also required to overcome friction but, unlike inertia effect, this force cannot be recovered again although the energy represented still exists somewhere as heat. Therefore, in an actual system the pressure in chamber B would be less than in chamber A by the amount of pressure used in overcoming friction along the way.

At all points in a system, therefore, the static pressure is always the original static pressure LESS any velocity head at the point in question and LESS the friction head consumed in reaching that point. Since both velocity head and friction represent energy which came from the original static head, and since energy cannot be destroyed, the sum of the static head, velocity head, and friction at any point in the system must add up to the original static head. This, then, is Bernoulli's principle, more simply stated: If a fluid flowing through a tube reaches a constriction, or narrowing of the tube, the velocity of fluid flowing through the constriction increases, and the pressure decreases. Bernoulli's principle governs the

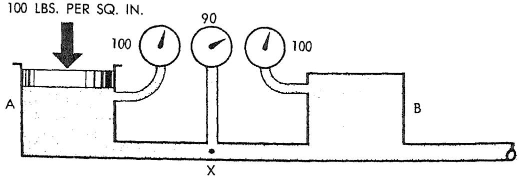

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Figure 1-7.—Relation of static and dynamic factors—Bernoulli's principle.

relationship of the static and dynamic factors concerning fluids, while Pascal's law governs the behavior of the static factors when taken by themselves.

BOYLE'S LAW

Compressibility is an outstanding characteristic of gases. The English scientist Robert Boyle was among the first to study this characteristic, which he called the "springiness of air." By direct measurement, he discovered that when the temperature of an enclosed sample of gas was kept constant and the pressure doubled, the volume was reduced to half the former value and, as the applied pressure was decreased, the resulting volume increased. From these observations, he concluded that for a constant temperature the product of the volume and pressure of an enclosed gas remains constant. This became Boyle's law, which is normally stated: "The volume of an enclosed dry gas varies inversely with its pressure, provided the temperature remains constant."

You can demonstrate Boyle's law by confining a quantity of gas in a cylinder which has a tightly fitted piston. Then apply force to the piston so as to compress the gas in the cylinder to some specific volume. If you double the force applied to the piston, the gas will compress to one-half its original volume, as indicated in figure 1-8.

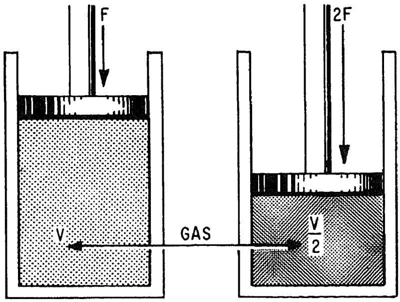

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Figure 1-8.—Gas compressed to half its original volume by a double force.

In formula or equation form (V = volume; P = pressure) when V_1 and P_1 are the original volume and pressure and V_2 and P_2 are the revised volume and pressure, this relationship may be expressed

$$V_1P_1 = V_2P_2$$

or

$$\frac{V_1}{V_2} = \frac{P_2}{P_1}$$

Example: 4 cubic feet of nitrogen are under a pressure of 100 psig. The nitrogen is allowed to expand to a volume of 6 cubic feet. What is the new gage pressure? Remember to convert gage pressure to absolute pressure by adding 14.7.

$$V_1P_1 = V_2P_2$$

Substitute

$$4 \times (100 + 14.7) = 6 \times P_2$$

$$P_2 = \frac{4 \times 114.7}{6}$$

$$P_2 = 76.47 \text{ psia}$$

(absolute pressure)

Convert absolute pressure to gage pressure

$$\begin{array}{r} 76.47 \\ -14.7 \\ \hline 61.77 \end{array} \text{ psig (gage pressure)}$$

Changes in the pressure of a gas also affect the density. As the pressure increases, its volume decreases; however, there is no change in the weight of the gas. Therefore, the weight per unit volume (density) increases. So it follows that the density of a gas varies directly as the pressure, if the temperature is constant.

Jacques Charles, a French scientist, provided much of the foundation for the modern kinetic theory of gases. He found that all gases expand and contract in direct proportion to the change in the absolute temperature, provided the pressure is held constant. In equation where V_1 and V_2 refer to the original and final volumes, and T_1 and T_2 indicate the corresponding absolute temperatures, this part of the law may be expressed

$$V_1 T_2 = V_2 T_1$$

or

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

Since any change in the temperature of a gas causes a corresponding change in volume, it is reasonable to expect that if a given sample of a gas were heated while confined within a given volume, the pressure should increase. By actual experiment, it was found that for each 1° C increase in temperature, the increase in pressure was approximately $\frac{1}{273}$ of the pressure at 0° C. Because of this fact, it is normal practice to state this relationship in terms of absolute temperature. In equation form, this part of the law becomes

$$P_1 T_2 = P_2 T_1$$

or

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

In words, this equation states that with a constant volume, the absolute pressure of an enclosed gas varies directly with the absolute temperature.

Examples of Charles' law: A cylinder of gas under a pressure of 1,800 psig at 20° C is left out in the sun and heats up to a temperature of 55° C. What is the new pressure within the temperature.)

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

or

$$\frac{1814.7 \text{ psia}}{2031.47 \text{ psia}} \quad \frac{292^\circ \text{ C absolute}}{328^\circ \text{ C absolute}}$$

NEWTON'S FIRST LAW

Newton's first law states that a body at rest tends to remain at rest, and a body in motion tends to remain in motion. This law can be demonstrated easily in every day use. For example, a parked automobile will remain motionless until some force causes it to move—a body at rest tends to remain at rest. The second portion of the law—a body in motion tends to remain in motion—can be demonstrated only in a theoretical sense. The same car placed in motion would remain in motion if all air resistance could be removed, if there were no friction at all encountered in the bearings, and if the surface on which the vehicle was traveling were perfectly level.

NEWTON'S SECOND LAW

Newton's second law states that an unbalance of force on a body tends to produce an acceleration in the direction of the force, and the acceleration, if any, is directly proportional to the force and inversely proportional to the mass of the body. This law can be explained by throwing a common softball. The force required to accelerate the ball to a rate of 50 ft/sec^2 would have to be doubled to obtain an acceleration rate of 100 ft/sec^2. However, if the mass of the ball were doubled, (do not confuse mass with weight) the original acceleration rate of 50 ft/sec^2 would be cut in half to 25 ft/sec^2. This law can be explained mathematically (A = acceleration; F = force; M = mass)

$$A = \frac{F}{M}$$

NEWTON'S THIRD LAW

Newton's third law states that for every action there is an equal and opposite reaction. You have demonstrated this law if you have ever jumped from a boat up to a dock or a beach. The boat moved opposite to the direction you jumped. (See fig. 1-9).

The recoil from firing a shotgun is another example of action-reaction. We can demonstrate this law with the same factors used in the second law in the equation

$$F = MA$$

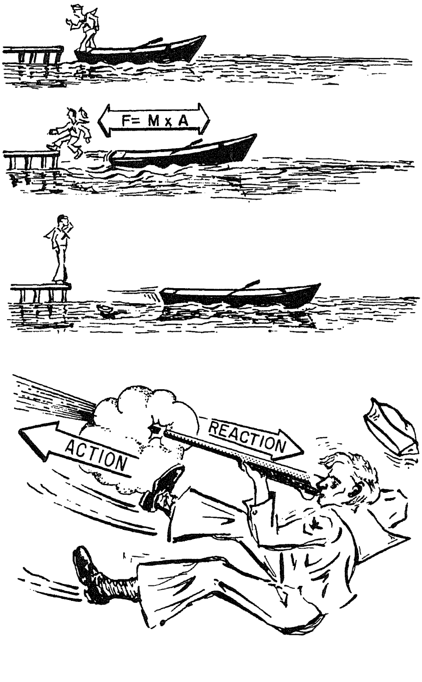

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Figure 1-9.—Newton's third law of motion.

In an airplane, this means the greater the mass of air handled by the engine, the more it is accelerated by the engine and the greater the force built up to thrust the plane forward. In a gas turbine, by adding more and progressively larger power turbine wheels, the thrust velocity can be absorbed by the turbine rotor and converted to mechanical energy.

BASIC ENGINE THEORY

Two factors are required for proper operation of a gas turbine. One is expressed by Newton's third law, and the other is the convergent-divergent process. Convergent means approaching nearer together, as the inner walls of a tube that is constricted. Divergent means moving away from each other, as the inner walls of a tube that flares outward.

Bernoulli's principle is used in this process. The venturi of the common automobile carburetor is a common example of Bernoulli's principle and the convergent-divergent process.

Now let us describe a practical demonstration of how a gas turbine operates. (see figure 1-10, foldout at the end of this chapter).

A blown-up ballon (fig. 1-10A) does nothing until the trapped air is released. The air escaping rearward causes the balloon to move forward (Newton's third law). (See fig. 1-10B).

If we could keep the balloon full of air, the balloon would continue to move forward. (See fig. 1-10C.)

If a fan or pinwheel is placed in the air stream, the pressure energy and velocity energy will cause it to rotate and it can then be used to do work. (See fig. 1-10D.)

By replacing the balloon with a tube or container (mounted in one place) and filling it with air from a fan or series of fans (located in the air opening and driven by some source) we can use the discharge air to turn a fan at the rear to do work. (See fig. 1-10E.)

If fuel is added and combustion occurs, we greatly increase both the volume of air (Charles' law) and the velocity with which it passes over

fan will produce (See fig. 1-10F.)

The continuous pressure created by the inlet fan, or compressor, prevents the hot gases from going forward.

Next, if we attach a shaft to the compressor and extend it back to a turbine wheel we have a simple gas turbine that can supply power to run its own compressor and still provide enough power to do useful work, such as drive a generator or propel a ship. (See fig. 1-10G.)

By comparing figure 1-10H with figure 1-10G you can see that a gas turbine is very similar to our balloon turbine. Recall the three basic parts of a gas turbine mentioned earlier:

1. Air is taken in through the air inlet duct by the compressor where it is raised in pressure and discharged into the combustion chamber.
2. Fuel is admitted into the combustion chamber by the fuel nozzle(s). The fuel-air mixture is ignited by igniter(s) and combustion occurs.
3. The hot and rapidly expanding gases are directed aft through the turbine rotor assembly where thermal and kinetic energy are converted into mechanical energy. The gases are then directed out through the exhaust duct.

THEORETICAL CYCLES

Let's dwell a little more on cycles and theory before we go into construction and design. A cycle is a process that begins with certain conditions, progresses through a series of additional conditions, and returns to the original conditions.

The gas turbine engine operates on the BRAYTON CYCLE. The OTTO CYCLE, used in gasoline engines, is one of constant volume while combustion occurs, and the Brayton cycle is one where combustion occurs at constant pressure. In reciprocating gasoline or diesel engines all events take place within one unit. That is, intake, compression and combustion as well as expansion and exhaust, take place within the cylinder. In gas turbines a specific component is designed to perform each function separately.

air is drawn in at constant pressure (L
As the piston moves upward the
increases and the volume decreases (L
Then the fuel is ignited which results i
increase in pressure (Line C-D).
pressure forces the piston downward,
in a drop in pressure and an increase i
(Line D-E). The exhaust valves open
the combustion charge with a rapid
pressure at constant volume (Line I
piston rises, forcing the exhaust gas
constant pressure (Line B-A). At po
cycle will begin again. Figure 1-11 g
shows how the Otto cycle begins, p
and returns to the same conditions.

The Brayton cycle can also be g
explained. (See fig. 1-11B.) Air enters
at atmospheric pressure and constan
(point A). As the air passes thro
compressor, it increases in press
decreases in volume (Line A-B). A
combustion occurs at constant press
the increased temperature causes
increase in volume (Line B-C). The
constant pressure and increased volu
the turbine and expand through it. As
pass through the turbine rotor, the ro
kinetic and thermal energy into m
energy. The expanding size of the
causes further increase in volume an

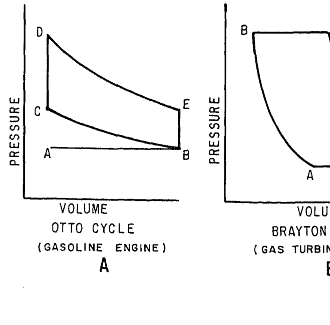

Figure 1-11.—The Otto cycle and Brayton

released through the stack with a large drop in volume and at constant pressure (Line D-A). The cycle is completed and commences again at point A.

In the reciprocating engine each event occurs in one location at independent intervals, i.e., no more than one event can occur at any one time. In the gas turbine engine all events—intake, compression, combustion, exhaust—are occurring simultaneously, but at different locations.

OPEN AND CLOSED CYCLES

Most internal-combustion engines operate on an open engine cycle, meaning the working fluid is taken in, used, and discarded. There are some gas turbines that operate on a semiclosed cycle. They use a regenerator such as used on the gas turbine ship *JOHN SERGEANT*. The gas turbines you will encounter in the Navy operate on the open cycle.

In the open cycle all the working fluid passes through the engine only once. The open cycle offers the advantages of simplicity and light weight.

The third classification of cycles is the closed cycle, where energy is added externally. The typical ship's steam plant is an example of a closed cycle system.

CONVERGENT-DIVERGENT PROCESS

There are several pressure, volume, and velocity changes that occur within a gas turbine during operation. The convergent-divergent process is an application of Bernoulli's principle. (If a fluid flowing through a tube reaches a constriction or narrowing of the tube, the velocity of the fluid flowing through the constriction increases and the pressure decreases. The opposite is true when the fluid leaves the constriction; velocity decreases and pressure increases.) Boyle's law and Charles' law also come into play during this process. Boyle's law: The volume of any dry gas varies inversely with the applied pressure, provided the temperature constant, the volume of dry gas varies directly with the absolute temperature.

Now, let's apply these laws to the gas turbine. Please refer to figure 1-12.

Air is drawn into the front of the compressor. The rotor is so constructed that the area decreases toward the rear. This tapered construction gives a convergent area (Area A). Each succeeding stage is smaller, which increases pressure and decreases velocity (Bernoulli).

Between each rotating stage is a stationary stage or stator. The stator partially converts high velocity to pressure and directs the air to the next set of rotating blades.

Because of its high rotational speed, the rotor imparts velocity to the air. Each pair of rotor and stator blades constitutes a pressure stage. Also, there is both a pressure increase at each stage, and a reduction in volume (Boyle).

This process continues at each stage until the air charge enters the diffuser. (See area B of figure 1-12.) There is a short area in the diffuser where no further changes takes place. As the air charge approaches the end of the diffuser, you will notice that the opening flares (diverges) outward. At this point, the air loses velocity, and increases in volume and pressure. Thus, the velocity energy has become pressure energy, while pressure through the diffuser has remained constant. The reverse of Bernoulli's principle and Boyle's law has taken place. The action of the compressor's continuously forcing more air through this section at a constant rate maintains constant pressure. Once the air is in the combustor, combustion takes place at constant pressure. After combustion there is a large increase in the volume of the air and combustion gases (Charles' law).

The combustion gases go rearward to area C partially by velocity imparted by the compressor and partially because area C is a lower pressure area. The end of area C is the turbine nozzle section. Here you will find a decrease in pressure and an increase in velocity. The high-velocity, high-temperature, low-pressure gases are directed through the inlet nozzle to the first stage of the turbine rotor (area D). The high-velocity, high-temperature gases cause the rotor to rotate

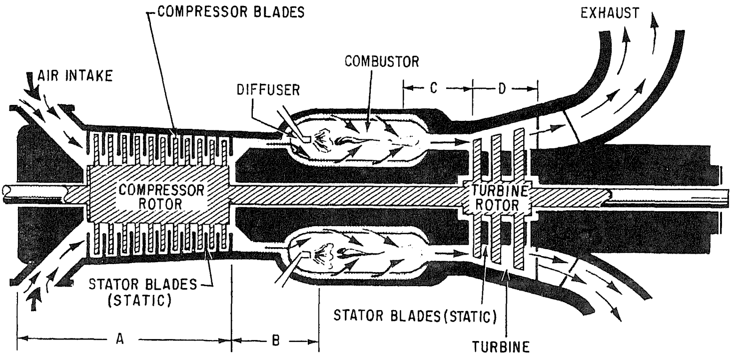

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Figure 1-12.—Convergent-divergent process.

by transferring velocity energy and thermal energy to the turbine blades. Area D is a divergent area. Between each rotating turbine stage is a static stage or "nozzle." The nozzles act much the same as the stators in the compressor.

A "nozzle" is a stator ring with a series of vanes which act as small nozzles to direct the combustion gases uniformly, and at the proper angle of attack, to the turbine blades. Due to the design of the nozzles, each succeeding stage imparts velocity to the gases as they leave the preceding stage, pass through the nozzle, and on to the succeeding stage. Each nozzle converts heat and pressure energy into velocity energy by controlling the expansion of the gas. Each small nozzle has a convergent area.

Each stage of the turbine is larger than the preceding one. The pressure energy drops are quite rapid; consequently, each stage must be larger to use the energy of a lower pressure, lower temperature, larger volume of gases. If more stages are used the rate of divergence will be less. Area D must diverge rapidly in proportion to the rate in which area A converges into area B. Atmospheric air is raised in pressure and velocity and lowered in volume in area A by the compressor. Each stage can only compress air about 1.2 times, so the rate is limited. However, in the turbine rotor (area D), the gases give up thermal and pressure energy and increase in volume through three stages. (If this did not happen rapidly, back pressure from area D would cause area C to become "choked"). The gases in the combustor would back up into the compressor. There they would disrupt airflow and cause a condition known as "surge," or compressor stall, which can destroy an engine in a matter of seconds. "Surge" will be explained in a later section.

The gases from the last turbine stage enter the exhaust duct where they are transmitted to the atmosphere. The leading portion of the exhaust duct is part of a divergent area. Further divergence reduces the pressure and increases the volume of the warm gases and aids in lowering the velocity. Depending on the length and size of the exhaust duct, the exhaust gases enter the atmosphere at or slightly above atmospheric pressure.

Now refer back to figure 1-11B. Air enters the intake at constant pressure (point A) and is compressed as it passes through the compressor (line A-B in fig. 1-11B and area A in fig. 1-12). Between the end of area B and the beginning of area C in figure 1-12, combustion occurs and volume increases (fig. 1-11B line B-C). As the gases pass through area D (fig. 1-12), the gases expand with a drop in pressure and an increase in volume (fig. 1-11B line C-D). The gases are discharged to the atmosphere through the exhaust duct at constant pressure (fig. 1-11B line D-A and fig. 1-12 exhaust). At this point you should have a clear understanding of how a simple gas turbine works.

ADIABATIC COMPRESSION

In the ideal gas turbine, the air enters the compressor and is compressed adiabatically. An adiabatic stage change is one in which there is no transfer of heat to or from the system while the process is occurring. In many real processes, adiabatic changes can occur when the process is performed rapidly. Since heat transfer is relatively slow, any rapidly performed process can approach an adiabatic state. Compression and expansion of working fluids are frequently achieved very nearly adiabatically.

Figure 1-13 depicts the pressure-temperature graph for a simple gas turbine. During operation the work produced by the compressor turbine

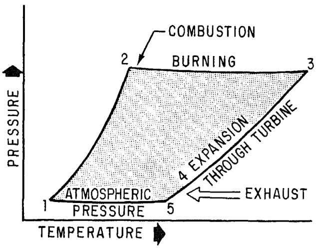

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Figure 1-13 —Gas turbine pressure temperature graph.

rotor is almost the same amount as the work required by the compressor. The mass flow available to the compressor turbine is about the same as the mass flow handled by the compressor. Therefore, the heat of compression will closely equal the heat of expansion, making allowances for factors such as bleed air, pressure of fuel added, and heat loss to turbine parts.

As the high-temperature, high-pressure gases enter the turbine section, they expand so rapidly that there is relatively little change in temperature of the gases. The net power available from the turbine is the difference between the turbine-developed power and the power required to operate the compressor.

EFFECT OF AMBIENT TEMPERATURE

The power and efficiency of a gas turbine engine is affected by both outside and inside variables. Air has volume which is directly affected by its temperature. As the temperature decreases, the volume of air for a given mass decreases and its density increases. Consequently, the mass weight of the air increases which in turn increases efficiency because less energy is needed to achieve the same compression at the combustion chambers. Also cooler air causes lower burning temperatures. The resulting temperatures extend turbine life. For example, a propulsion gas turbine is operating at 100% gas generator speed with 100% power turbine speed at an ambient (external air) temperature of 70° F. If the temperature were increased to 120° F, the volume of air would increase and the mass weight would decrease. Since the amount of fuel added is limited by the inlet temperature the turbine will withstand, the mass weight flow cannot be achieved; the result is a loss of net power available for work. The plant may be able to produce only 90% to 95% of its rated horsepower.

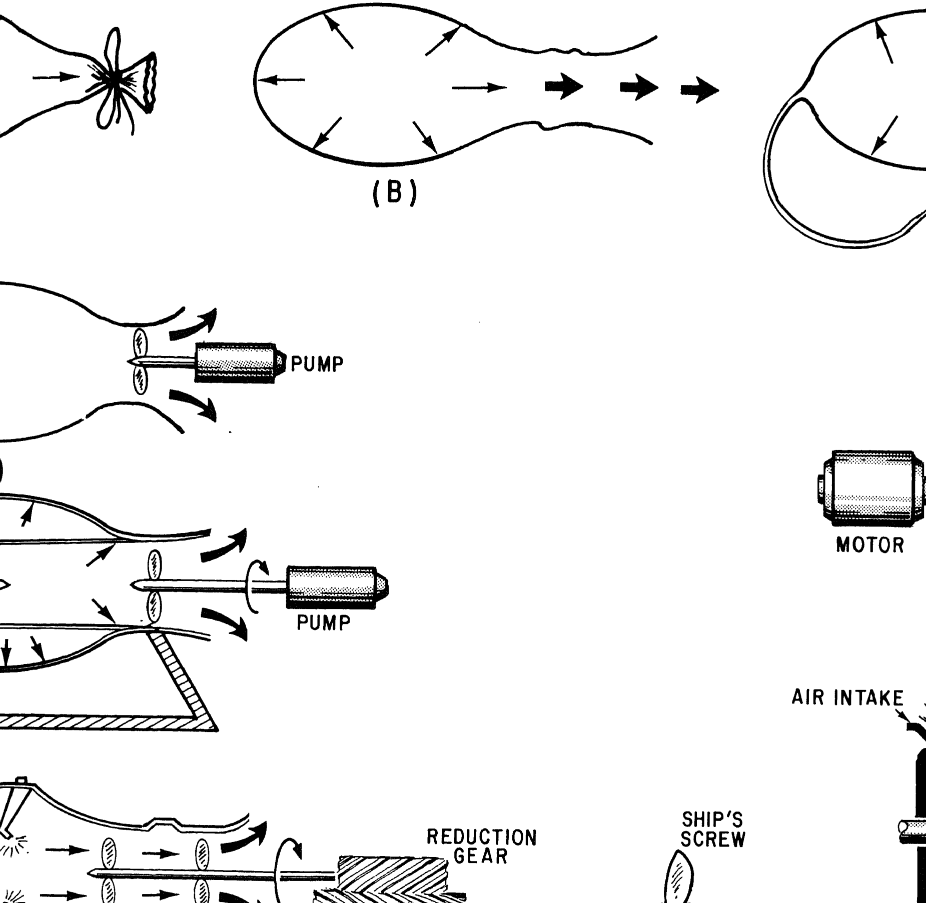
On the other hand, if the ambient temperature were to drop to 0° F, the volume of air would decrease, and the mass weight would increase. Since the mass weight is increased and heat transfer is better at higher pressure, less fuel

is needed to increase volume; the result is a heavier mass of air at the required volume. This situation produces quite an efficient power plant with a gas generator speed of 85% to 90% and a power turbine speed of 100%. In the case of a constant speed engine such as used on a generator set, the differences in temperature will show up on exhaust gas temperature and, in some cases, on the load the engine will pull. For instance, on a hot day of 120° F, the engine on a 300 kW generator set may be able to pull only 275 kW due to limitations on exhaust or turbine inlet temperature. On a day with 0° F ambient temperature, the same engine will pull 300 kW and have an exhaust or turbine inlet temperature that may well be more than 100° Fahrenheit lower than average. Here again, less fuel is needed to increase volume and a greater mass weight flow, which in turn makes the plant more efficient.

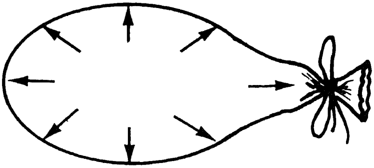
COMPRESSOR CLEANLINESS

Another factor that will have a great effect on performance is the condition of the compressor. A clean compressor is essential to efficiency and reliability. During operation at sea the compressor will ingest salt spray that is present in the air. Over a period of time, this salt will build up in the compressor. Salt buildup is relatively slow and will occur more on the stator blades and the compressor case than on rotating parts. Centrifugal force tends to sling salt contaminants off the rotor blades. Also, oil rapidly increases contamination of the compressor. Any oil ingested into the engine coats the compressor with a film which traps any dust and other foreign matter suspended in the air. The dust and dirt absorb more oil which traps more dirt, etc. If left unattended, the buildup of contamination will lead to a choking of the compressor and a restricted airflow. In turn, gradually more fuel is required so the gas temperatures will rise until loss of power and damage to the turbine may result. Contamination, if not controlled, can lead to a compressor surge during light off.

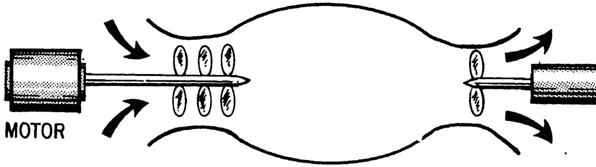
In this chapter you have been introduced to many terms and concepts that will form the basis for the discussions and descriptions which follow in the text. If you do not feel you understand the temperature-pressure relationships in a simple gas turbine at this time, you would do well to re-read the last part of this chapter before continuing on to the material which follows.



(B)
PUMP
MOTOR
PUMP
AIR INTAKE
SHIP'S
SCREW
REDUCTION
GEAR



(A)



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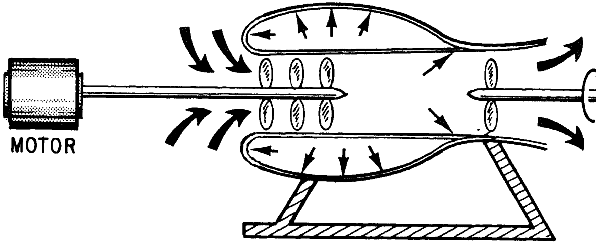

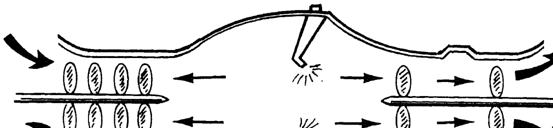

CHAPTER 2

ENGINE TYPES AND CONSTRUCTION

There are several different types of gas turbines in use: SINGLE SHAFT, SPLIT SHAFT, and TWIN SPOOL. Of these, the single shaft and split shaft are the most common in use in naval vessels. We will mention the twin spool type and give a brief description. The USCG Hamilton class cutters use the Pratt-Whitney FT-4 twin spool gas turbine.

In current U.S. Navy service the single shaft engine is used primarily for driving ship's service generators, and the split shaft engine is used for main propulsion as a variety of speed ranges are encountered.

Figure 2-1 is a block diagram of a single shaft gas turbine. In the engine illustrated, the power output shaft is connected directly to the same turbine rotor that drives the compressor. In most cases, there is a speed decreaser or reduction gear between the rotor and the power output shaft; however, there is still a mechanical connection throughout the entire engine.

In the split shaft engine (fig. 2-2), there is no mechanical connection between the gas-generator turbine and the power turbine. With this type of engine the output speed can be varied by varying the generator speed. Also, under certain conditions the gas generator can run at a reduced rpm and still provide maximum power turbine rpm which greatly improves fuel economy and also extends the life of the gas

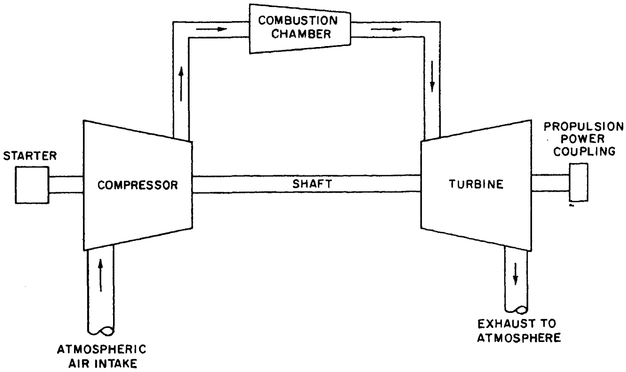

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Figure 2-1.—Single shaft engine.

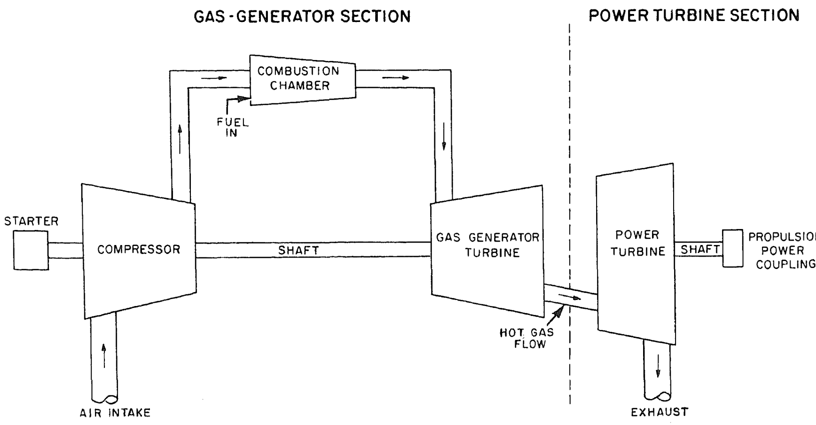

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Figure 2-2.—Split shaft engine.

generator turbine. The starting torque required is lowered appreciably due to the fact that the power turbine, reduction gears, and output shaft remain stationary until the gas generator reaches approximate idle speed. Another feature is that in a multishaft marine propulsion plant where one design (clockwise rotation or counterclockwise rotation) of gas generator can be used on either shaft, the gas generator rotates only one way; however, the power turbine can be made to rotate either way by changing the power turbine wheel and nozzles. The arrangement shown in figure 2-2 is typical for propulsion gas turbines aboard the DD-963 and FFG-7 class ships.

Another type of turbine is the twin spool, sometimes referred to as a multistage gas turbine. In the twin spool engine there are two separate compressors and two separate turbine rotors. They are referred to as L.P. compressor and turbine rotor and H.P. compressor and turbine rotor. (See fig. 2-3.) The L.P. compressor and turbine are connected by a shaft which runs through the hollow shaft that connects the H.P. turbine to the H compressor. The starter drives the H.P. assem during light off. The power turbine functi the same as in the split shaft engine. A lar volume of air can be handled as compared t single or split shaft engine; however, the eng has more moving parts, and the increase overall dimensions and complexity make engine less desirable for ship's propulsion t the split shaft engine.

CLASSIFICATION BY COMPRESSOR TYPE

Gas turbines are also classified compressor type, according to the direction the flow of air through the compressor. The t principal types are centrifugal flow and a flow. The centrifugal compressor draws in ai the center or eye of the impeller and accelera it around and outwards. In the axial flow eng the air is compressed while continuing original direction of flow parallel to the axis the compressor rotor.

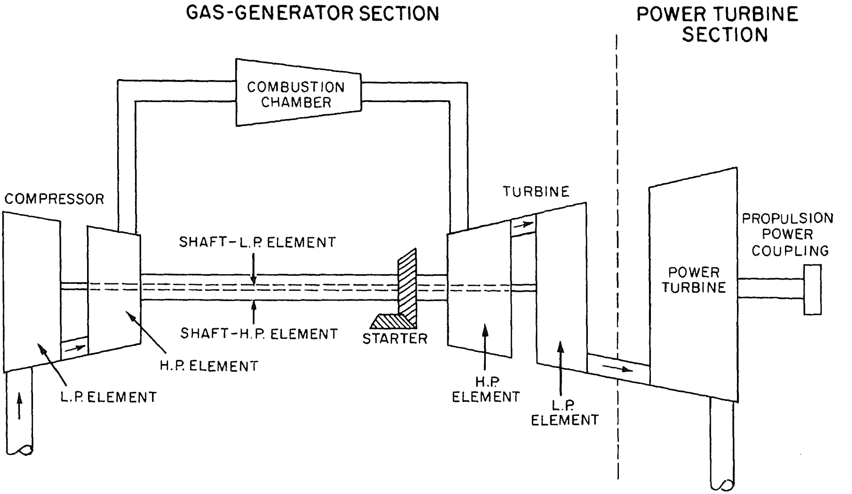

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Figure 2-3.–Twin spool engine.

CENTRIFUGAL COMPRESSOR

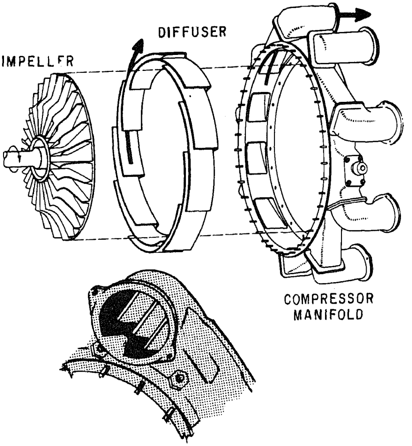
The centrifugal compressor is usually located between the accessory section and the combustion section. The basic compressor section consists of an impeller, diffuser, and compressor manifold. The diffuser is bolted to the manifold and often the entire assembly is referred to as the diffuser. For ease of understanding we shall treat each unit separately.

The impeller may be either single entry or dual entry (fig. 2-4). The principal differences between the single entry and dual entry are the size of the impeller and the ducting arrangement. The single entry impeller permits convenient ducting directly to the inducer vanes as opposed to the more complicated ducting needed to reach the rear side of the dual entry type. Although slightly more efficient in receiving air, single entry impellers must be of greater diameter to provide sufficient air which increases the overall diameter of the engine.

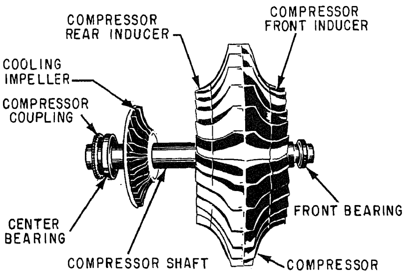
Dual entry impellers are smaller in diameter and rotate at higher speeds to ensure sufficient airflow. Most gas turbines of present day design use the dual entry compressor to reduce engine diameter. A plenum chamber is also required for dual entry compressors since the air must enter the engine at almost right angles to the engine axis. The air must surround the compressor at positive pressure before entering the compressor to give positive flow.

Principles of Operation

The compressor draws in the entering air at the hub of the impeller and accelerates it



(A) ELEMENTS OF A SINGLE ENTRY CENTRIFUGAL COMPRESSOR; AIR OUTLET ELBOW WITH TURNING VANES FOR REDUCING AIR PRESSURE LOSSES.



(B) DUAL ENTRY COMPRESSOR

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Figure 2-4.—Centrifugal compressors.

radially outward by means of centrifugal force through the impeller. It leaves the impeller at a high velocity low pressure and flows through the diffuser. (See fig. 2-4A.) The diffuser converts the high velocity low pressure air to low velocity with high pressure. The compressor manifold diverts the flow of air from the diffuser, which is an integral part of the manifold, into the combustion chambers. In this design the manifold has one outlet port for each combustion chamber.

The outlet ports are bolted to an outlet elbow on the manifold. The outlet ports ensure that the same amount of air is delivered to each combustion chamber.

The outlets are known by a variety of names but, regardless of the terminology used, the elbows change the airflow from radial flow to axial flow, and the diffusion process is completed after the turn. Each elbow contains from two to four turning vanes to efficiently perform the turning process and to reduce air pressure losses by presenting a smooth turning surface.

The impeller is usually fabricated from forged aluminum alloy, heat-treated, machined, and smoothed for minimum flow restriction and turbulence. Some types of impellers are made from a single forging. In other types the inducer vanes are separate pieces.

Centrifugal compressors may achieve efficiencies of 80% to 84% at pressure ratios of 2.5:1 to 4:1 and efficiencies of 76% to 81% at pressure ratios of 4:1 to 10:1.

Advantages: rugged, simple in design, relatively light in weight and develops high-pressure ratio per stage.

Disadvantages: large frontal area, lower efficiency, and difficulty in using two or more stages due to air loss that will occur between stages and seals.

AXIAL FLOW COMPRESSORS

There are two main types of axial compressors (fig. 2-5). One is the drum type and the other is the disc type. The drum type rotor consists of rings that are flanged to fit one against the other, wherein the entire assembly

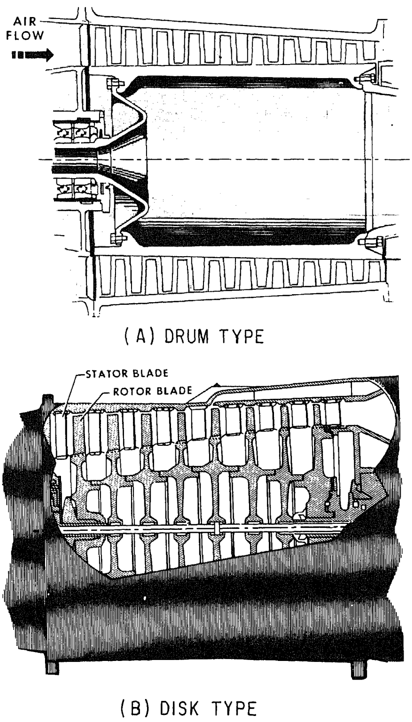

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Figure 2-5.—Compressor rotors.

may then be held together by through bolts. This type of construction is satisfactory for low-speed compressors where centrifugal stresses are low.

The disc type rotor consists of a series of discs machined from aluminum forgings, shrunk over a steel shaft, with rotor blades dovetailed into the disc rims. Another method of rotor construction is to machine the discs and shaft bolt steel stub shafts on the front and rear of the assembly for providing bearing support surfaces and splines for joining the turbine shaft. The disc type rotors are used almost exclusively in all present-day high-speed engines and are the type referred to in this manual.

The purpose of the axial compressor is the same as the centrifugal type, to take in ambient air and increase the velocity and pressure and discharge the air through the diffuser into the combustion chamber.

The two main elements of an axial flow compressor are the rotor and stator (fig. 2-6).

The rotor has fixed blades which force the air rearward much like an aircraft propeller. Behind each rotor stage is a stator. The stator directs the air rearward to the next rotor stage. Each consecutive pair of rotor and stator blades consitutes a pressure stage.

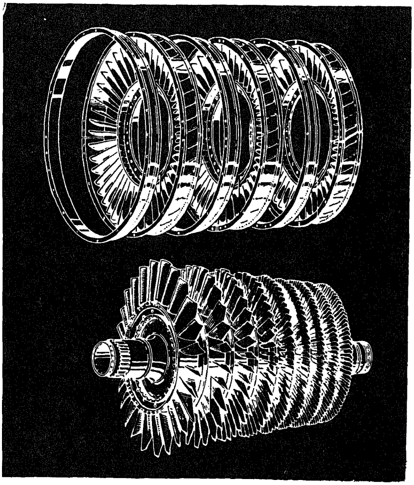

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Figure 2-6.—Stator and rotor components of an axial

The action of the rotor at each stage increases compression of the air at each stage and accelerates it rearward. By virtue of this increased velocity, energy is transferred from the compressor to the air in the form of velocity energy. The stators at each stage act as diffusers, partially converting high velocity to pressure.

The number of stages required is determined by the amount of air and total pressure rise required. The greater the number of stages, the higher the compression ratio. Most present day engines have 8 to 16 stages, depending on air requirements.

Construction

The rotor and stators are enclosed in the compressor case. Present day engines use a case that is horizontally divided into upper and lower halves. The halves are normally bolted together with either dowel pins or fitted bolts located at various points to ensure proper alignment to each other and in relation to other engine assemblies which bolt to either end of the compressor case.

On some older design engines the case is a one-piece cylinder open on both ends. The one-piece compressor case is simpler to manufacture; however, any repair or detailed inspection of the compressor rotor is impossible. The engine must be removed and taken to a shop where it is disassembled for repair or inspection of the rotor or stators. On many engines with the split case, either the upper or lower case can be removed with the engine in place for maintenance and inspection.

The compressor case is usually made of aluminum or steel. The material used will depend on the engine manufacturer and the accessories attached to the case. The compressor case may have external connections made as part of the case. These connections are normally used to bleed air during starting and acceleration or at low-speed operation.

DRUM-TYPE CONSTRUCTION.–The drum-type rotor (fig. 2-5A) consists of rings that are flanged to fit one against the other, w the entire assembly may then be held tc by through bolts. The drum is one diamete its full length. The blades and stators v length from front to rear, and the comp case tapers accordingly. This typ construction is satisfactory for low compressors where centrifugal stresses ar

DISC TYPE CONSTRUCTION disc-type rotor (fig. 2-5B) consists of a se discs machined from aluminum forgings, s over a steel shaft. Another method of construction is to machine the discs and from a single aluminum forging and then steel stub shafts on the front and rear assembly to provide bearing support su and splines for joining the turbine shaf blades vary in length from entry to dis due to a progressive reduction in the a working space (drum to casing) toward th by the increase in the rotor disc diamete disc-type rotors are used almost exclusively present-day, high-speed engines.

ROTOR BLADES.–The rotor blad usually made of stainless or semistainless Methods of attaching the blades in the rot rims vary in different designs, but the commonly fitted into discs by either bul 2-7A) or fir tree (fig. 2-7B) type root blades are then locked by means of grub-s peening, lockwires, pins, or keys.

Compressor blade tips are reduce cutouts, which are referred to as "profiles." These profiles allow "rubbing" occurs when rotor blades come into c with the compressor or housing without c serious damage to the blade or housing.

Some manufacturers use a ring which a spacer for the stators and as a wear s when the blade tips come in contact wi ring.

Another method of preventing ex rubbing while maintaining minimum clear to metal-spray the case and stators.

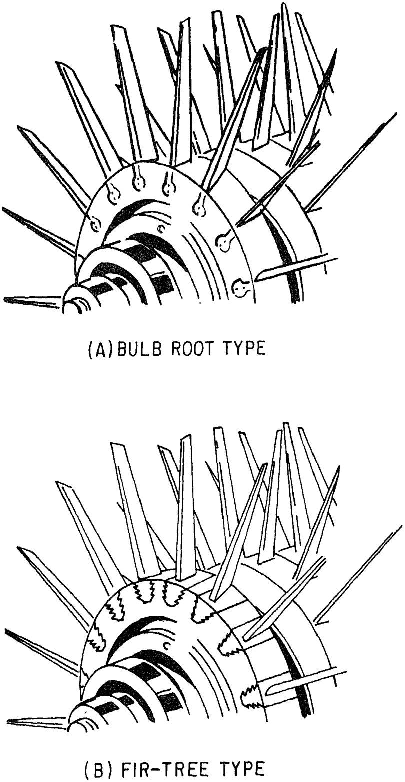

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Figure 2-7.—Rotor blades.

"squealer tips" on the blades and vanes (fig. 2-8) contact the sprayed material. The abrasive action of the blade tip prevents excessive rubbing while obtaining minimum clearance.

The primary causes of rubbing are an excessively loose blade or a malfunction of a

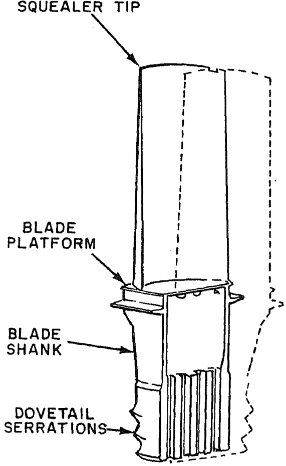

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Figure 2-8.—Blade with squealer tip.

compressor support bearing which allows the compressor rotor to drop.

Large compressors have loose fitting blades on the first several stages which move during acceleration to minimize vibration while passing through critical speed ranges. Once up to speed, centrifugal force locks the blades in place and little or no movement occurs. There is also movement of the blades during rundown. On a clean engine some of the blades may have as much as 1/4-inch radial movement, and you may hear a tinkling sound during rundown.

Large compressor rotors, with long blades on the first stage, have a piece made onto the blade called a midspan platform (fig. 2-9). The platform gives some radial support to the blades during acceleration, which is needed because of the length and amount of movement of the blades.

STATORS.—The stator vanes project radially toward the rotor axis and fit closely on

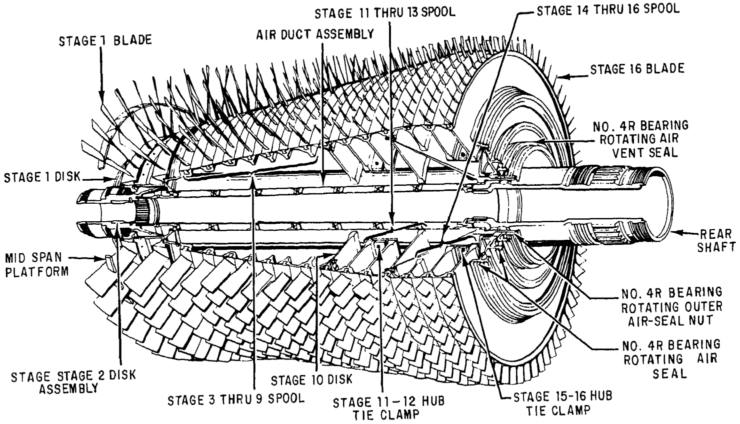

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Figure 2-9.—Compressor rotor, LM 2500 engine.

either side of each stage of the rotor. The function of the stators is twofold. (1) They receive air from the air inlet duct or from each preceding stage of the rotor and then deliver the air to the next stage or to combustors at a workable velocity and pressure. (2) The stators also control the direction of air to each rotor stage to obtain the maximum possible compressor-blade efficiency. The stator vanes are usually made of steel with corrosion- and erosion-resistant qualities. Frequently, the vanes are shrouded by a band of suitable material to simplify the fastening problem. The vanes are welded into the shrouds, and the outer shrouds are secured to the inner wall of the compressor case by radial retaining screws.

Some manufacturers machine a slot in the outer shrouds and run a long, thin key the length of the compressor case. The key is held in place by retaining screws to prevent the stators from turning within the case. This method is used when a one-piece compressor case is slid over the compressor and stator assembly.

Each pair of vanes in a stator acts as a diffuser. They utilize the divergent principle: the outlet of the vane area is larger than the inlet. This diverging area takes the high-velocity, low-pressure air from the preceding rotor stage, converts it to a low-velocity, high-pressure airflow and then directs it at the proper angle to the next rotor stage. The next rotor stage will restore the air velocity that was lost due to the pressure rise. The next stator will give a further pressure rise. This process continues for each stage in the compressor.

A 1.2X-pressure rise is about as much as a single stage can handle. Higher pressure rises result in higher diffusion rates with excessive turning angles, which cause excessive air instability, hence low efficiency. Although the pressure RATIO remains unchanged across each stage, the pressure RISE varies across each stage. The following is an example. A 13-stage compressor has a pressure ratio at each stage of 1.1 and an ambient inlet of 14.7. What is the

final pressure? What is the overall pressure ratio?

$$\underline{\text{STAGE 1}} \quad \underline{\text{STAGE 2}} \quad \underline{\text{STAGE 3}}$$
$$14.7 \times 1.1 = 16.17 \times 1.1 = 17.79 \times 1.1$$

$$\underline{\text{STAGE 4}} \quad \underline{\text{STAGE 5}} \quad \underline{\text{STAGE 6}}$$
$$= 19.57 \times 1.1 = 21.52 \times 1.1 = 23.67 \times 1.1$$

$$\underline{\text{STAGE 7}} \quad \underline{\text{STAGE 8}} \quad \underline{\text{STAGE 9}}$$
$$= 26.04 \times 1.1 = 28.65 \times 1.1 = 31.51 \times 1.1$$

$$\underline{\text{STAGE 10}} \quad \underline{\text{STAGE 11}} \quad \underline{\text{STAGE 12}}$$
$$= 34.66 \times 1.1 = 38.13 \times 1.1 = 41.94 \times 1.1$$

$$\underline{\text{STAGE 13}}$$
$$= 46.13 \times 1.1 = 50.75$$

FINAL PRESSURE = 50.75 psi
INITIAL PRESSURE = 14.7 psi

$$\text{Compression ratio} = \frac{50.73}{14.7} = 3.45{:}1$$

The pressure rise across the first stage is:

16.2 psi pressure at back of 1st stage
-14.7 psi pressure at front of 1st stage
1.5 psi pressure rise across 1st stage

Pressure rise across the last stage is:

50.75 pressure at back of 13th stage
-46.13 pressure at front of 13th stage
4.62 pressure rise across 13th stage

The pressure ratio is the same for each stage, but the pressure rise is greater at the last stage. The velocity and density have an effect on pressure rise through a compressor. Compression ratio will increase or decrease with engine speed. The compressor inlet temperature will also have an effect on pressure rise through the compressor.

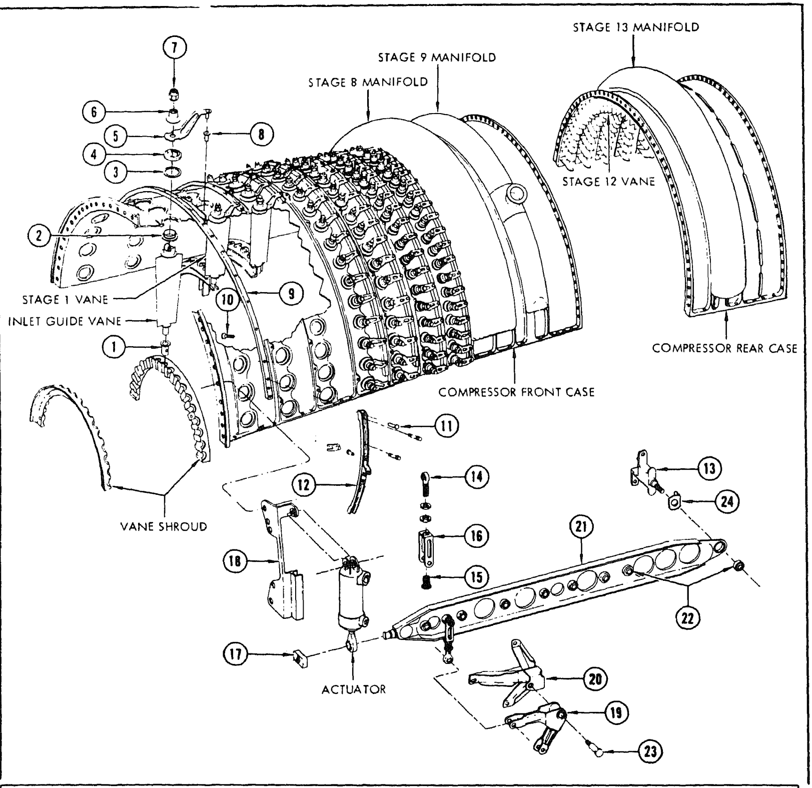
Preceding the stators and the first stage of the compressor is a row of vanes known as IGV's (inlet guide vanes). The function of the IGV's varies somewhat, depending on the size of the engine and the air-inlet construction. On smaller engines the air inlet is not totally in line with the first stage of the rotor. The IGV straightens the airflow and directs it to the first-stage rotor. On large engines the IGV's are variable and move with the variable stators. The variable IGV on large engines directs the airflow at the proper angle to reduce drag on the first stage rotor. Variable IGV's achieve the same purposes as variable stator vanes (VSV's).

Small and medium engines have stationary stators. On large engines the pitch of the vanes on several stators can be changed. For example the first 6 stators of a 16-stage rotor may be variable such as those used in the General Electric LM 2500 engine (fig. 2-10).

The variable stators are controlled by compressor inlet temperature (CIT) and engine power requirements. They are moved by mechanical linkages that are connected to the fuel-control governor. Variable stators have a twofold purpose. (1) They are positioned at various angles depending on compressor speed to ensure the proper angle of attack between the compressor blades. Varying the blade angle helps to maintain maximum compressor efficiency over the operating speed range of the engine. This is important in variable speed engines such as those used for main propulsion. (2) The variable stators on large engines virtually eliminate "compressor surge." Surge (fig. 2-11) results when the airflow stalls across the compressor blades; that is, air is not smoothly compressed into the combustion and turbine section. Stalling may occur over a few blades or a section of some stages, and, if enough flow is interrupted, pressure may surge back through the compressor. This occurrence can be minor or very severe with possible damage to the turbine resulting.

All of the air in the combustor then may be used for combustion instead of only the primary air. Lack of cooling air may cause extreme temperatures which burn the combustor and turbine section. (By a change in the angle of the stators and the use of bleed valves, the airflow through the compressor is ensured and compressor surge can be almost totally prevented.)

Constant-speed engines, such as those used to drive generators, normally do not use variable



LEGEND:

1. VANE SHROUD BUSHING (IGV, 1 & 2)
2. FLANGED BUSHING
3. WASHER
4. SPACER (COLOR CODED)
5. LEVER ARM
6. SLEEVE
7. LOCKNUT
8. SLEEVE
9. ACTUATION RING SEGMENT
10. ACTUATION RING SPACER
11. LINE-UP PIN
12. CONNECTING LINK
13. ACTUATION LEVER MOUNT
14. ROD END AND BEARING
15. PUSH ROD
16. ACTUATION LEVER CLEVIS
17. ACTUATION LEVER GUIDE
18. ACTUATOR AND GUIDE BRACKET
19. FEEDBACK BELLCRANK
20. FEEDBACK BELLCRANK BRACKET
21. VANE ACTUATION LEVER
22. SELF ALIGNING BEARINGS
23. SHOULDER BOLT
24. SPACER

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Figure 2-10.—Compressor stator, LM 2500 engine.

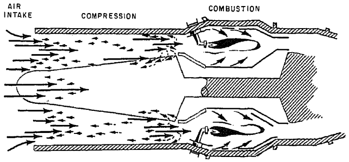
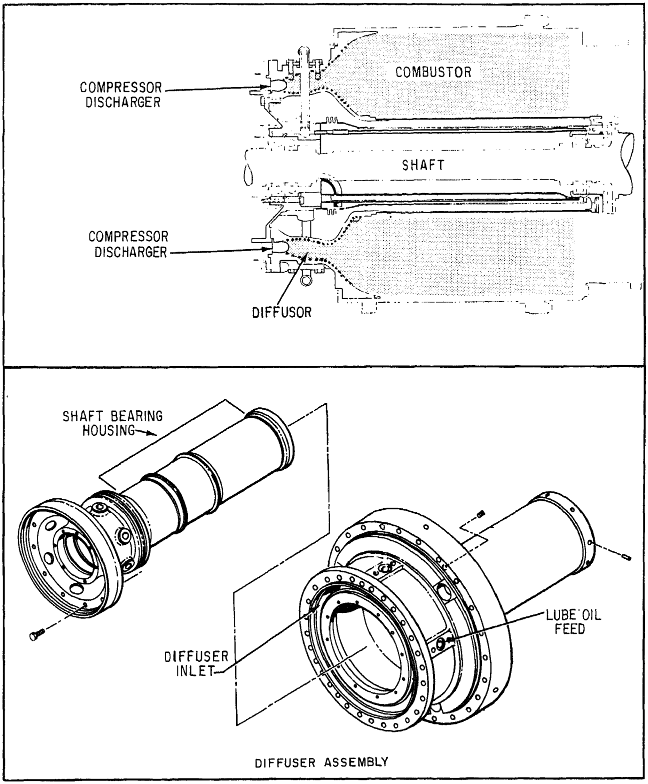


Figure 2-11.—Compressor surge. 277.16

stators because they are designed to operate at 100% rpm all the time. The proper fuel schedule and air bleed valves are adequate to prevent or minimize compressor surge.

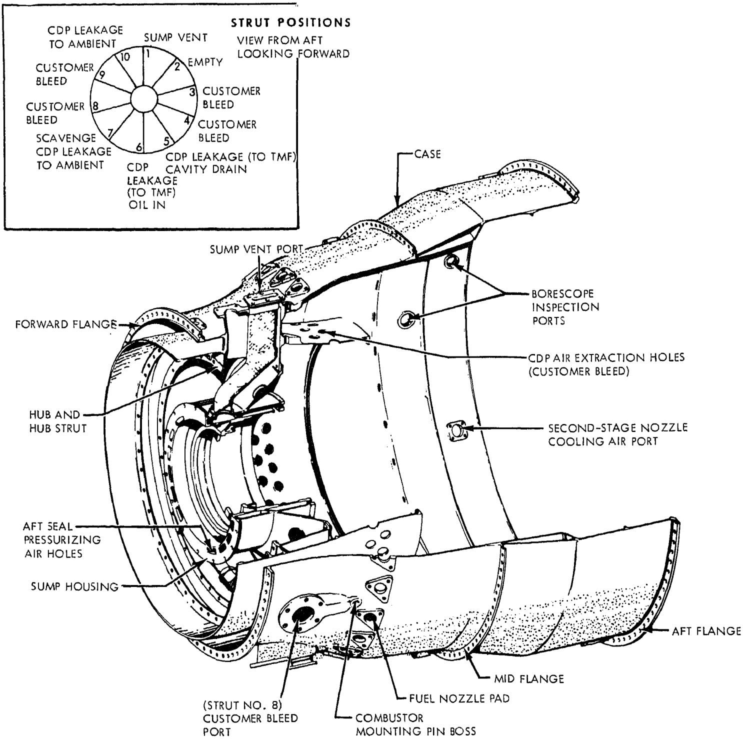
DIFFUSER.–The diffuser (fig. 2-12) plays a very important role in the construction and operation of a gas turbine. The diffuser is located between the compressor and the



combustion chamber and, on some engines, it acts as a support for the rear compressor bearing. It also provides a means of support to the inner and outer combustion liners. The combustor case may be bolted to one end of the diffuser along with the rear end of the compressor case.

The struts of the diffuser may be cast with passages through which (1) various bearings are lubricated, (2) the bearing sump is scavenged, and (3) the bearing cavity is vented either to the sump, to an air-oil separator, or to the atmosphere. On large engines the compressor rear frame along with the cowl assembly performs the same functions as the diffuser assembly in a small engine. (See fig. 2-13 and 2-14.)

The diffuser section operates on Bernoulli's Theorem using the covergent-divergent principle.



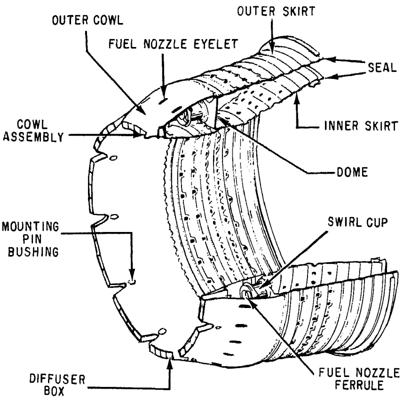


Figure 2-14.—Combustor.

The diffuser takes the discharge of compressor air, straightens the flow of air, and distributes it evenly to the combustor for uniform combustion and even temperatures throughout the combustor. The area across the diffuser is a diverging area. That is, the aft end of the diffuser is larger than the forward end. Due to the increase in area there is a decrease in velocity with an increase in volume at a constant pressure and temperature (Boyle's Law and Charles' Law). There is also an increase in static pressure within the combustor.

COMBUSTION CHAMBERS.—The combustion chambers have presented one of the biggest problems in gas turbines. The extreme stresses and temperatures encountered are not experienced in other types of internal-combustion engines. The liners are subjected to temperatures that range from ambient to as high as 4,000° F in a matter of seconds.

The combustion chamber must have the capability to operate over a wide range of operating conditions, to withstand a high rate of burning, to have a minimum pressure drop, to be light in weight, and to have minimum bulk.

The two common materials used in combustion chambers are Inconel for the liners or flame tubes and stabilized stainless for the combustor case.

The inner and outer liners or shrouds are perforated with many holes and slots through their length. Air is admitted through these holes for combustion to protect the liner and to cool the gases at the chamber outlet. The design of the flame tube is very critical to the life and efficiency of the engine.

The combustion chamber must ensure that the combustion process is complete over a variety of ranges. Poor design can cause flameouts, unburned fuel, or stratified fuel to reach the turbine section which can result in overheating and damage to the turbine section.

There are two types of flow passages used in combustion chambers—the counterflow path and through-flow path. The counterflow system is rarely found in modern engines but was used primarily with very early design engines, such as the Whittle engine. The through-flow path is used in practically all modern engines. In the through-flow path the gases pass through the combustion section without a change in direction.

There are three types of combustion chambers: (1) can type, (2) annular type, and (3) can-annular type. The can-type chamber is used primarily on engines that have a centrifugal compressor. The annular and can-annular are used on axial flow compressors.

Can-Type Chamber.—The can-type combustion system consists of individual liners and cases mounted around the axis of the engine. Each chamber (fig. 2-15) contains a fuel nozzle. This arrangement makes removing a chamber easy; however, it is a bulky arrangement and makes for a structurally weak engine. The outer casing is welded to a ring that directs the gases into the turbine nozzle. Each of the casings is linked to the others with a short

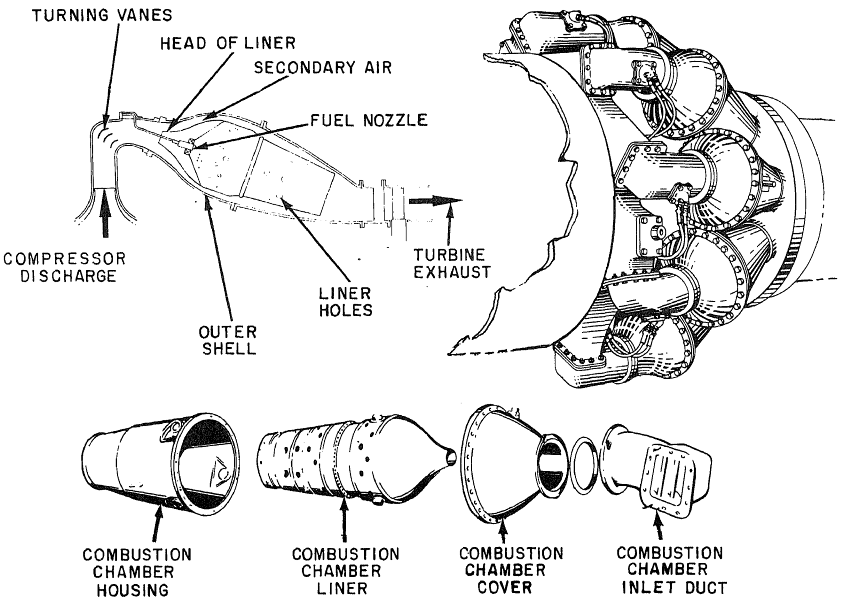


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Figure 2-15.—Elements of tubular or can-type combustion chamber.

tube which ensures that combustion occurs in all of the burners during light off. Inside each of these tubes is a flame tube that joins an adjacent inner liner.

Annular Chamber.—The annular combustion chamber is usually found on axial flow engines. It is probably one of the most popular combustion systems in use. The construction consists of a housing and liner the same as the can-type.

The great difference is in the liner. On large

attached at the turbine section and diffuser section.

The chamber may contain one or more liners, one outside the other in the same radial plane, hence the double-annular combustion chamber (fig. 2-16).

The dome of the liner has small slots and holes to admit primary air and to impart a swirling motion for better atomization of fuel. There are also holes in the dome for the fuel nozzles to extend through into the combustion

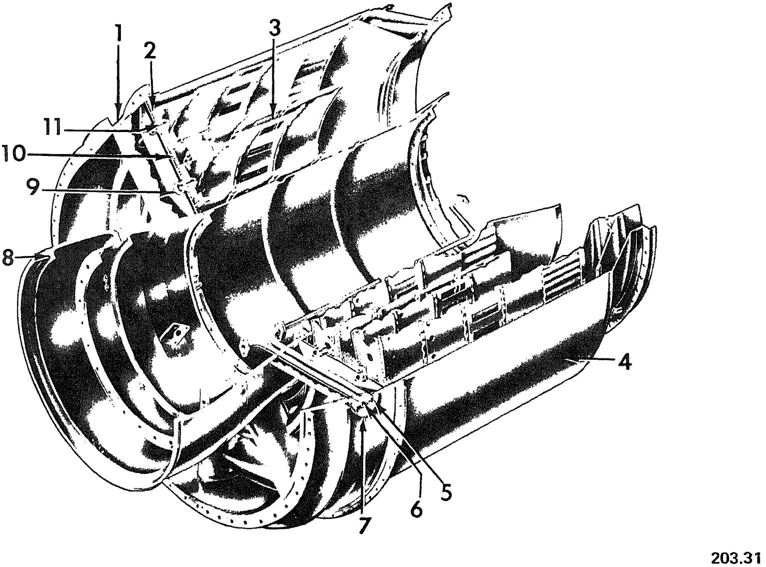

Figure 2-16.—Double-annular combustion chamber.

combustor case, and the inner liner prevents flame from contacting the turbine shaft housing.

Large holes and slots are located along the liners (1) to admit some cooling air into the combustion space towards the rear of the space to help cool the hot gases to a safe level, (2) to center the flame, and (3) to admit the balance of air for combustion. The gases are cooled enough to prevent warpage of the liners.

The space between the liners and the case and shaft housing form the path for secondary air. The secondary air provides film cooling of the liners and the combustor case and shaft housing. At the end of the combustion space and just prior to the first-stage turbine nozzle, the secondary air is mixed with the combustion gases to cool the temperature to prevent warping and melting of the turbine section.

The annular-type combustion chamber is a very efficient system that minimizes bulk and can be used most effectively in limited space. There are some disadvantages, however. On some engines, the liners are one-piece and cannot be removed without engine disassembly. Also, engines that utilize a one-piece combustor dome must be disassembled to remove the dome.

Can-Annular Chamber.—The can-annular combustion chamber combines some of the features of both the can and the annular burners.

The can-annular chamber design is a result of the split-spool compressor concept. Because of the problems encountered with a long shaft and with one shaft within the other, a different chamber was designed to fill a shorter space and still perform all the necessary functions.

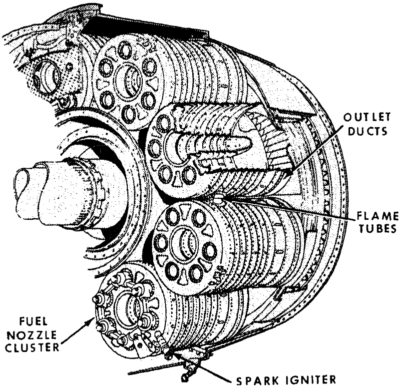

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Figure 2-17.—Can-annular combustion chamber components and arrangement.

Individual cans are placed inside an annular case. The cans are essentially individual combustion chambers (fig. 2-17) with concentric rings of perforated holes to admit air for cooling. On some models each can has a round perforated tube which runs down the middle of the can. The tube carries additional air which enters the can through the perforations to provide more air for combustion and cooling. The effect is to permit more burning per inch of can length than could otherwise be accomplished.

Fuel nozzle arrangement varies from one nozzle in each can to several nozzles around the perimeter of each can.

The cans have an inherent resistance to buckling because of their small diameter. Each can has two holes which are opposite each other near the forward end of the can. One hole has a collar called a flame tube. When the cans are assembled in the annular case, these holes and their collars form open tubes between adjacent cans so that a flame passes from one can to the next during engine starting.

The short length of the can-annular chamber provides minimal pressure drop of the gases between the compressor outlet and the flame area. Another feature of the can-annular engine is the greater structural strength it gets from its short combustor area. Maintenance is simple. Just slide the case back and remove any one burner for inspection or repair, rather than the entire assembly. Another advantage is that the relatively cool air in the annular outer can tends to reduce the high temperatures of the inner cans. At the same time, this air blanket keeps the outer shell of the combustion section cooler.

NOZZLES (TURBINE).—The stator element of the turbine section is known by a variety of names of which the three most common are turbine nozzle vanes, turbine guide vanes, and nozzle diaphragm. In this text, turbine stators are usually referred to as nozzles. The turbine nozzle vanes are located directly aft of the combustion chambers and immediately forward of, and between the turbine wheels.

Turbine nozzles have a two-fold function. First, after the combustion chamber has introduced the heat energy into the mass airflow and delivered it evenly to the nozzles, the nozzles prepare the mass flow for harnessing of power through the turbine rotor. The stationary blades or vanes of the turbine nozzles are contoured and set at such an angle that they form a number of small nozzles which discharge the gas as extremely high-speed jets; thus, the nozzle converts a varying portion of the heat and pressure energy to velocity energy which can then be converted to mechanical energy through the rotor blades.

The second purpose of the turbine nozzle is to deflect the gases to a specific angle in the direction of turbine wheel rotation. Since the gas flow from the nozzle must enter the turbine blade passageway while it is still rotating, it is essential to aim the gas in the general direction of turbine rotation.

The elements of the turbine nozzle assembly consists of an inner shroud and an outer shroud between which are fixed the nozzle vanes. The number of vanes varies with different types and

sizes of engines. Figure 2-18 illustrates typical turbine nozzles featuring loose and welded vane fits.

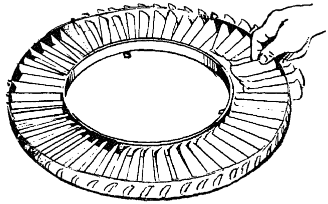
The blades or vanes of the turbine nozzle may be assembled between the outer and inner shrouds or rings in a variety of ways. Although the actual elements may vary slightly in their configuration and construction features, there is one characteristic peculiar to all turbine nozzles; that is, the nozzle vanes must be constructed to allow for thermal expansion. Otherwise, there will be severe distortion or warping of the metal components because of rapid temperature variances.

Thermal expansion of turbine nozzles is accomplished by one of several methods. In one method the vanes are assembled loosely in the supporting inner and outer shrouds (fig. 2-18A). Each of the vanes fits into a contoured slot in the shrouds which conform with the airfoil shape of the vanes. These slots are slightly larger than the vane to give a loose fit. For further support the inner and outer shrouds are encased by an inner and an outer support ring which add strength and rigidity. These supports also permit removal of the nozzle vanes as a unit; otherwise, the vanes could fall out of the shrouds as the shrouds are removed.

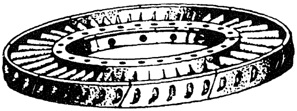
Another method to allow for thermal expansion is to fit the vanes into inner and outer shrouds. In this method the vanes are welded or riveted into position (fig. 2-18B). To provide for the inevitable thermal expansion, either the inner or the outer shroud ring is cut into segments. The saw cuts dividing the segments will allow sufficient expansion to prevent stress and warping of the vanes.

The basic types of construction of nozzles are the same for all types of turbines. The convergent-divergent principle (Bernoulli's principle) is used to increase gas velocity.

The turbine nozzles are made of high-strength steel to withstand the direct impact of the hot, high-pressure, high-velocity gases from the combustor. The nozzle vanes must also resist erosion from the high-velocity gases passing over them.



(A)



(B)

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Figure 2-18.—(A) Turbine nozzle vane assembly with loose fitting vanes; (B) Turbine nozzle vane assembly with welded vanes.

Increasing the inlet temperature of the gases by approximately 750°F makes it possible to achieve an approximate 100% increase in specific horsepower. However, nozzles do not stand up for long to the higher temperatures. Different methods of increasing nozzle endurance have been tried over the years.

One method that was tried was to coat the nozzle with a ceramic coating. Higher temperatures were achieved, but the different expansion rates of the the steel and the ceramic caused the coating to break away over a period of time. Experiments are still being conducted, even so far as to use an entirely ceramic nozzle.

Another means of withstanding high temperatures is to use space-age metals. However, extreme costs of the metals prohibit commercial production of such nozzles.

Still another method, which is in wide use today in large engines, is to use air-cooled nozzle

blades. Compressor bleed air is fed through passages to the turbine where it is directed to the nozzle. The air cools both the turbine (discussed later) and the nozzle. The nozzle may also be cooled by air admitted from the outer perimeter of the nozzle ring. The method of getting the air in is determined by the manufacturer.

The nozzle vanes are made with many small holes or slots on the leading and trailing edges (fig. 2-19). Air is forced into the nozzle and out through the slots and holes, cooling the vane as it passes through. The air is discharged into the hot gas stream, passing through the remainder of the turbine section, and then out the exhaust duct.

Figure 2-20 compares temperature of an air-cooled vane against a nonair-cooled vane.

Cooling air is used primarily in the H.P. turbine section. The temperature of the gases is at an acceptable level by the time the gases re the L.P. turbine section where metals in curr usage will last for long periods of time.

Seals installed between the nozzle entra shroud and the turbine shaft may be pressuri with bleed air to minimize interstage leakage the gases as they pass through the turbine.

THE TURBINE ASSEMBLY

In theory, design, and operat characteristics, the turbines used in gas turb engines are quite similar to the turbines used steam plant. The gas turbine differs from steam turbine chiefly in (1) the type of blad material used, (2) the means provided cooling the turbine shaft bearings, and (3) lower ratio of blade length to wheel diameter

The terms gas generator turbine and po turbine are used to differentiate between turbines. The gas generator turbine powers gas generator and accessories. The power turb powers the screw through the reduction gear shafting.

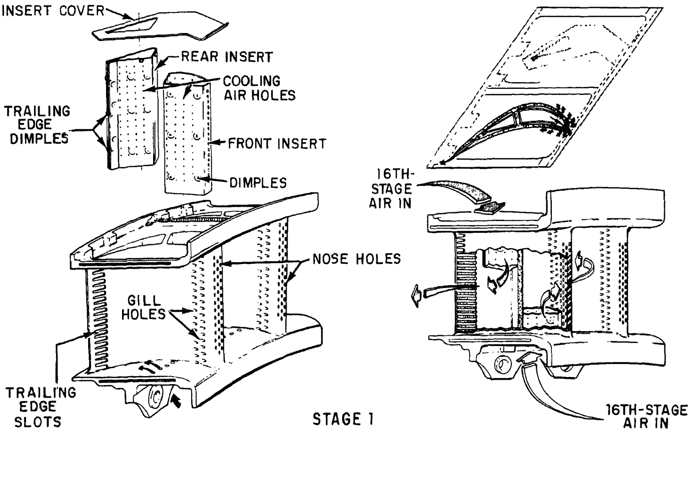

Figure 2-19.—First-stage gas generator turbine nozzle cooling.

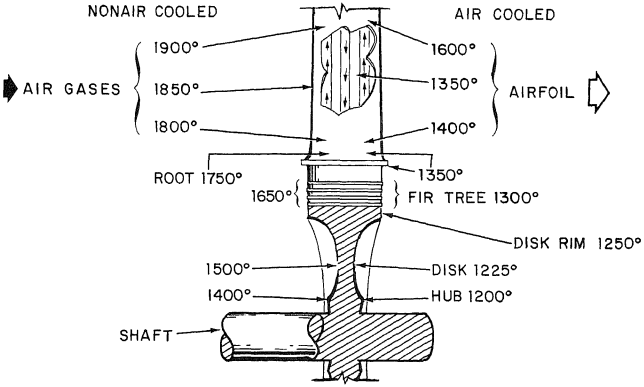

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Figure 2-20.—Cooling comparisons between an air-cooled vane and a nonair-cooled vane.

The turbine which drives the compressor of a gas turbine engine is located directly behind the combustion chamber outlet. The turbine consists of two basic elements, the stator or nozzle, and the rotor. Part of a stator element is shown in figure 2-21; a rotor element is shown in figure 2-22.

The rotor element of the turbine consists of a shaft and bladed wheel(s). The wheel(s) are attached to the main power transmitting shaft of the gas turbine engine. The jets of combustion gas leaving the vanes of the stator element act upon the turbine blades and cause the turbine wheel to rotate in a speed range of approximately 3,600 to 42,000 rpm. The high rotational speed imposes severe centrifugal loads on the turbine wheel, and at the same time the high temperature (1,050° to 2,300° F) results in a lowering of the strength of the material. Consequently, the engine speed and temperature must be controlled to keep turbine operation within safe limits. The operating life of the turbine blading usually determines the life of the gas turbine engine.

The turbine wheel is a dynamically balanced unit consisting of blades attached to a rotating disk. The disk in turn is attached to the rotor shaft of the engine. The high-velocity exhaust gases leaving the turbine nozzle vanes act on the blades of the turbine wheel, causing the assembly to rotate at a very high rate of speed.

The turbine disk is referred to as such when in an unbladed form. When the turbine blades are installed, the disk then becomes the turbine wheel. The disk acts as an anchoring component for the turbine blades. Since the disk is bolted or welded to the shaft, it enables the blades to transmit to the rotor shaft the energy they extract from the exhaust gases.

The disk rim is exposed to the hot gases passing through the blades and absorbs considerable heat from these gases. In addition, the rim also absorbs heat from the turbine blades by conduction. Hence, disk rim temperatures normally are quite high and well above the temperatures of the more remote inner portion of the disk. As a result of these temperature gradients, thermal stresses are added to the stresses caused by rotation.

Various means are provided to relieve, at least partially, the aforementioned stresses. One

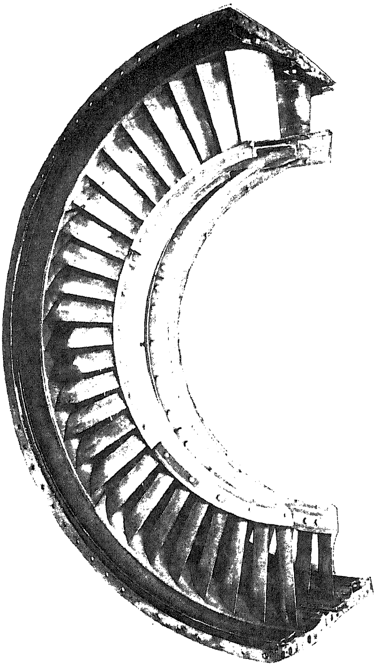

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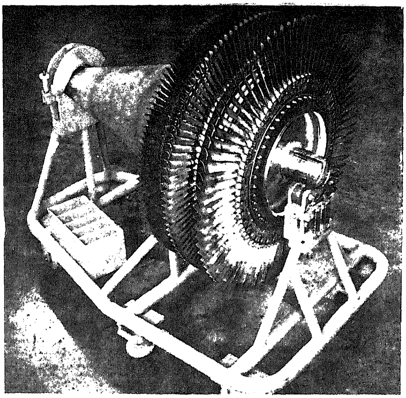
Figure 2-21.—Stator element of turbine assembly.



147.145
Figure 2-22.—Rotor element of turbine assembly.

such means is the incorporation of an auxiliary fan somewhere ahead of the disk, usually rotor shaft-driven, which forces cooling air back into the face of the disk.

Another method of relieving the thermal stresses of the disk follows as incidental to blade installation. By notching the disk rims to conform with the blade root design, the disk is made adaptable for retaining the turbine blades, and at the same time space is provided by the notches for thermal expansion of the disk.

The turbine shaft is usually fabricated from low-alloy steel. It must be capable of absorbing high torque loads, such as exerted when a heavy axial flow compressor is started.

The methods of connecting the shaft to the turbine disk vary. One method used is welding. The shaft is welded to the disk, which has a butt or protrusion provided for the joint. Another method is by bolting. This method requires that the shaft have a hub which matches a machined surface on the disk face. The bolts then are inserted through holes in the shaft hub and anchored in tapped holes in the disk. Of the two methods the latter is more common.

The turbine shaft must have some means for joining the compressor rotor hub; this is usually accomplished by making a splined cut on the forward end of the shaft. The spline fits into a coupling device between the compressor and the turbine shafts. If a coupling is not used, the splined end of the turbine shaft may fit into a splined recess in the compressor rotor hub. The centrifugal compressor engines use the splined coupling arrangement almost exclusively, while axial compressor engines may use either of these described methods.

There are various ways of attaching turbine blades. Some ways are similar to the way

compressor blades are attached. The most satisfactory method used is the fir-tree design shown in figure 2-23.

The blades are retained in their respective grooves by a variety of methods. Some of the more common methods are peening, welding, locking tabs and riveting. Figure 2-24 shows a typical turbine wheel utilizing riveting for blade retention.

The peening method of blade retention is used quite frequently, and its use may be applied in various ways. Two of the most common applications of peening are described in the following paragraphs.

One peening method requires you to grind a small notch in the edge of the blade fir-tree root prior to installing the blade. After you have installed the blade in the disk, the notch will fill with the disk metal, which is "flowed" into it through a small punchmark which you make in the disk adjacent to the notch. The tool you use for this job is similar to a centerpunch and is usually manufactured locally.

Another peening method is to construct the root of the blade in such a way that it contains all the elements necessary for its retention. This method, illustrated in figure 2-25, shows that the blade root has a stop made on one end of the root so that the blade may be inserted and removed in one direction only, while on the opposite end is a tang. You peen this tang over to secure the blade in the disk.

Turbine blades may be either forged or cast, depending on the metal they are made of.

Turbine blades are usually machined from individual forgings. Various materials are used in the forging. Speed and operating temperatures are important factors that decide which materials go into the turbine blades.

Large engines utilize an air-cooled blading arrangement on the gas generator turbine. (See fig. 2-26.) Compressor discharge air is continuously fed through passages along the

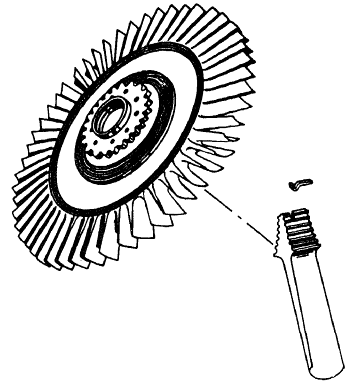


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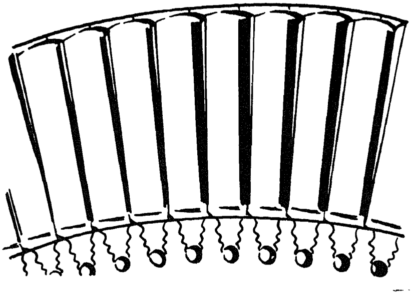
Figure 2-23.—Turbine blade with fir-tree design and tab lock method of blade retention.



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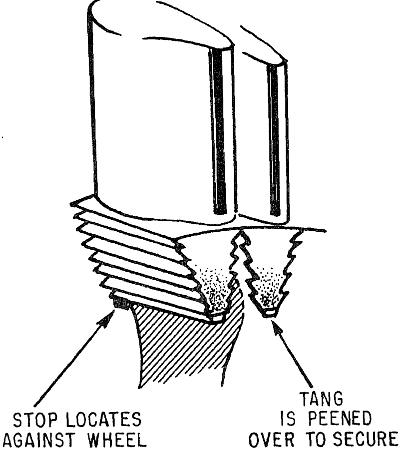

203.39
Figure 2-25.—Turbine bucket, featuring peening method of blade retention.

second-stage turbine wheels directs the co
air along the face of the disk for cooling o
disk. The air is then directed through slots i
fir-tree portion of the disk, into slots in
blade fir-tree, and up through holes in the b
to cool the blades. (See figure 2-27.)

Cooling of the turbine wheel and b
reduces thermal stresses on the rot
members. The turbine nozzles are
air-cooled. By cooling the stationary
rotating parts of the turbine section, h
turbine inlet temperatures are permissible v
allow for more power, a more efficient en
and longer engine life.

POWER TURBINES

Turbine wheels are used three diff
ways.

1. The aircraft jet turbine is designed s
turbine extracts only enough energy fron
gases to run the compressor and accessories
2. In the solid-wheel turbine, such
turboprop airplane or ship's service gene
engine, as much energy as possible is extr

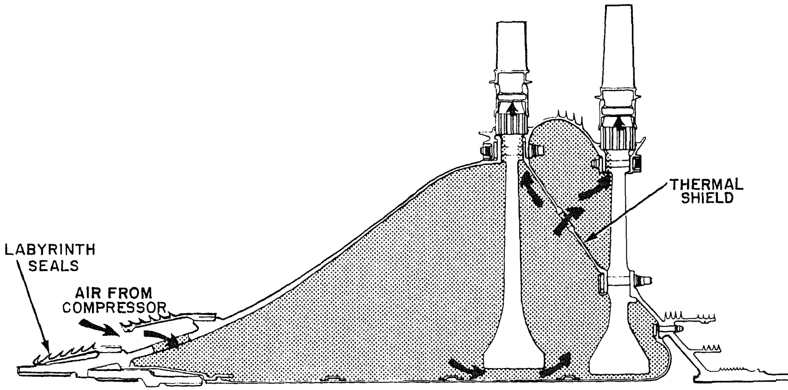

Figure 2-26.—Gas generator turbine rotor cooling.

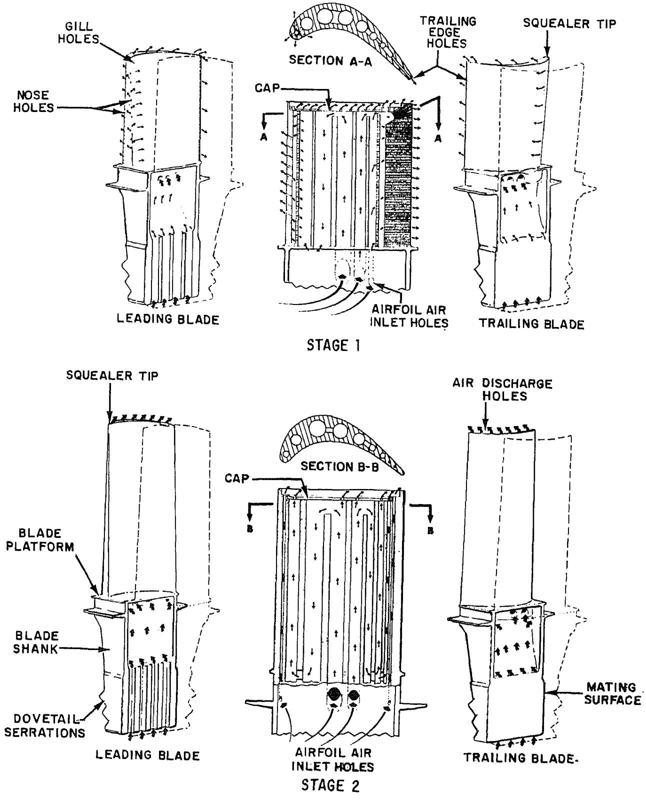

Figure 2-27.—Gas generator turbine rotor blade cooling.

from the gases to turn the turbine which provides power for the compressor, accessories, and the airplane propeller or the ship's generator. These engines are designed to run at 100% specified rpm all the time. The location of the mechanical connection between the turbine wheel and the reduction gear on the compressor front shaft depends on the design of the installation. Normally, there is no means to disconnect a ship's service generator from its gas turbine except by disassembly. This setup is used for generators since there can be no slippage between the engine and the generator.

3. Currently used Marine propulsion engines use a combination of the two engine

stage high-pressure rotor that drives the compressor and accessories.

The power turbine (fig. 2-28) is a multistage turbine located behind the gas generator turbine. There is no mechanical connection between the two turbines. The power turbine is connected to a reduction gear through a clutch mechanism.

a reverse gear is used to change direction o vessel.

Some ships that have two sets of engin counterrotating power turbines, i.e., p turbines on one shaft rotate cloc while the turbines on the other counterclockwise. This arrangement elim

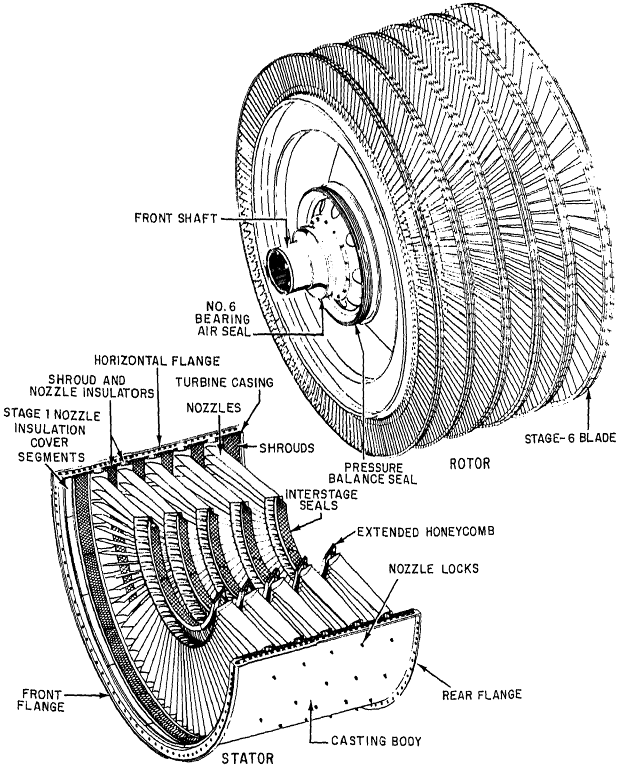

Figure 2-28.—Power turbine.

the use of a V-drive. The gas generator portion rotates in the same direction for both sets of engines. Directional rotation of the power turbine is determined by the blade angle of the wheel and the nozzles in the power turbine section. On large ships where different length propeller shafts are permitted, the engine(s) can be mounted to the other end of the reduction gear to achieve counterrotation of the screw.

By varying the gas generator speed, the output speed of the power turbine can be controlled. Since only a portion of the energy is used to drive the compressor, the plant can be operated very efficiently. For example, on a cold day it is possible to have 100% power turbine specified rpm with 80% to 90% gas generator specified rpm. The variables discussed earlier in the chapter account for this situation.

The power turbine is constructed much like the gas generator turbine. The most noticeable differences are (1) the absence of cooling air, and (2) the power turbine blades have interlocking shroud tips for low vibration levels. Honeycomb shrouds in the turbine case mate with the blade shrouds to provide a gas seal and to protect the case from the high-temperature gas. Two popular methods of blade retention are the bulb-type and the dovetail.

MAIN BEARINGS

The main bearings have the critical function of supporting the main engine rotor. For the most part, the number of bearings necessary for proper engine support is decided by the length and weight of the engine rotor. The length and weight are directly affected by the type compressor used in the engine. Naturally, a split-spool axial compressor will require more support than a simple centrifugal compressor engine. The minimum number of bearings required will be three, while some of the later models of split-spool axial compressor engines will require six or more.

The gas turbine rotors are usually supported by either ball or roller bearings, but some engines use sleeve bearings. Hydrodynamic or slipper-type bearings are receiving some attention for use on turbine powerplants where operating rotor speeds approach 45,000 rpm and where excessive bearing loads during operation are anticipated. (See fig. 2-29). In general, ball or roller antifriction bearings are preferred largely because they offer little rotational resistance; facilitate precision alignment of rotating elements; are relatively inexpensive; may be easily replaced; can withstand high momentary overloads; are simple to cool, lubricate, and maintain; can accomodate both radial and axial loads; and are relatively resistant to elevated temperatures. The main disadvantages are their vulnerability to foreign matter damage and their tendency to fail without appreciable warning.

Usually, the ball bearings are positioned on the compressor or turbine shaft so that they may absorb any axial (thrust) loads or radial loads. The roller bearings are better equipped to support radial loads than thrust loads because they present a larger working surface. Therefore, they are used primarily for this purpose.

The elements of a typical ball or roller bearing assembly include a bearing support housing, which must be strongly constructed and supported to carry the radial and axial loads of the rapidly rotating rotor. The bearing housing usually contains oil seals to prevent the oil's leaking from its normal path of flow, and it also delivers lubricating oil to the bearing, usually through spray nozzles.

On modern engines, the bearing is mounted in a sump. The bearing sump has a line through which the lube oil is scavenged back to the sump. The bearing sump is also vented to prevent either a pressure or vacuum. The vent goes either to the atmosphere or to an air-oil separator.

OIL SEALS

The three types of oil seals that are common in gas turbines are: (1) lip-type seal, (2) labyrinth/windback, and (3) carbon ring.

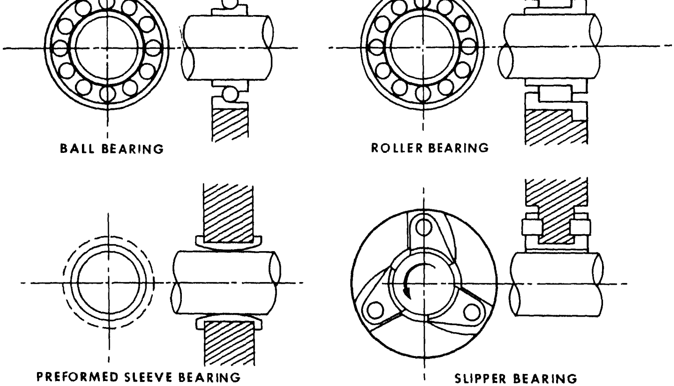

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Figure 2-29.—Types of main bearings used for gas turbine rotor support.

LIP-TYPE SEAL

The lip-type seal (fig. 2-30) is used to prevent leakage in one direction only. A metal frame is covered with a synthetic material, usually neoprene. The neoprene is somewhat smaller than the shaft. The elastic ability of the neoprene will allow the shaft to slide through the seal. The seal is molded with a lip to retain a spring around the center. The spring keeps a snug fit around the shaft. The construction of the lip-type seal allows for some very slight misalignment and for axial movement of the shaft. The lip seals are used where relatively low speeds and temperatures are encountered.

The disadvantages of the lip-type seals are that (1) they will seal against only little or no fluid pressure and (2) they are easily damaged by a burr on the shaft, or dirt, either of which will tear the seal and cause leakage.

LABYRINTH/WINDBACK SEAL

The labyrinth/windback seal combines a rotating seal having oil slingers and a serrated surface with a stationary seal having windback threads and a smooth rub surface. (See figure 2-31). The oil slingers throw oil into the windback threads which direct the oil back to the sump area. The serrations cut grooves into the smooth surface of the stationary seal to maintain close tolerances throughout a large temperature range. This seal allows a small

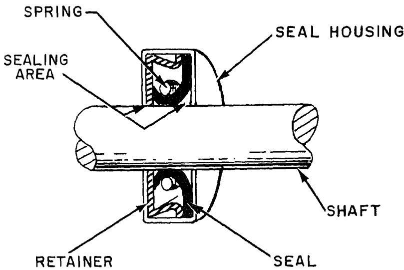

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Figure 2-30.—Lip-type seal.

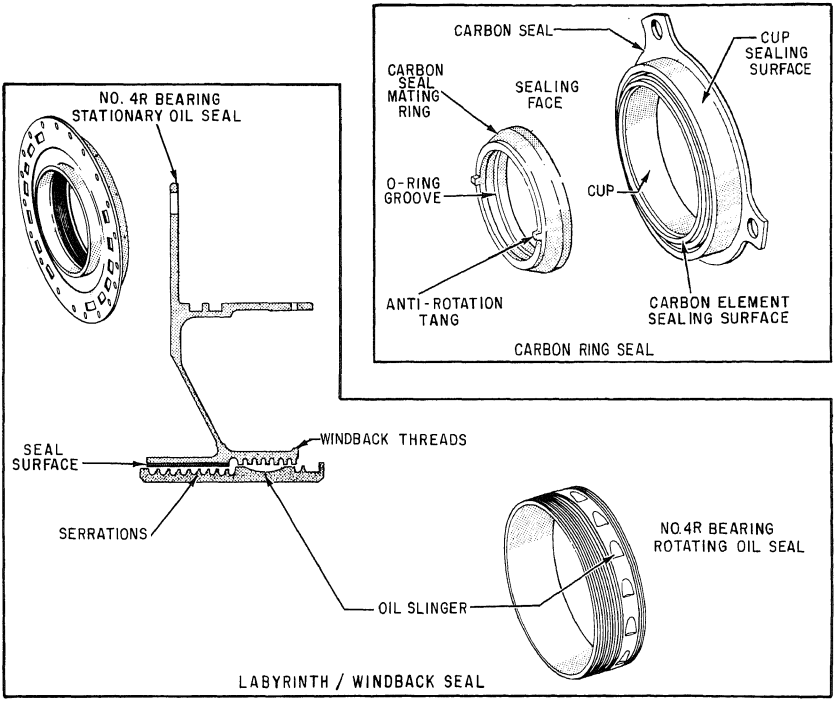

Figure 2-31.—Typical oil seals.

amount of seal pressurization air to leak into the sump, thereby preventing oil leakage.

CARBON RING SEAL

The carbon seal consists of a stationary spring-loaded, carbon sealing ring and a rotating, highly polished steel mating ring. It prevents oil in the gearbox from leaking past the drive shafts of the starter, fuel pump, and auxiliary drive pad.

Another form of the carbon seal is also in use. The carbon rings are not spring-loaded. They move freely around the shaft and seal axially against their housing. When the engine is up to speed, the rings center themselves radially in the housing. Compressor bleed air is forced in between the carbon rings. The air pressure is forced out along the shaft in both directions. The pressure prevents oil from entering the compressor or turbine and combustion gases from reaching the bearings. The main disadvantage of this type seal is minor oil leakage during start up and run down as the oil pump moves oil before there is sufficient airflow

overhaul hours before oil accumulation will have any harmful effects.

O-RING PACKING

The O-ring packing is used extensively throughout the engine. O-rings, sometimes called preformed packing, are used to seal between stationary parts. There is a variety of materials used in O-rings. We will only mention that the type and temperature of the fluids coming in contact with the ring determine the type of material used to make the O-ring.

AIR SYSTEMS

Air is used for many different functions on the gas turbine engine. The primary airflow and the secondary airflow designate the major systems.

PRIMARY AIRFLOW

The gas generator compressor draws air from the ship's inlet, through the enclosure inlet plenum, inlet screen inlet duct, and the front frame. After being compressed, the primary air enters the combustion section where some of it is mixed with fuel, and the mixture is burned. The remainder of the primary air is used for centering the flame in the combustor and some parts of the gas generator turbine. The primary air becomes part of the hot combustion gases. Some of the energy in the hot combustion gas is used to turn the gas generator turbine rotor which is coupled to, and turns, the compressor rotor. Upon leaving the gas generator turbine section, the gas passes into the power turbine section. Most of the remaining energy is extracted by the power turbine rotor which drives the high-speed, flexible-coupling shaft. The shaft provides the power for the ship's drive system. The gas exits from the power turbine through the turbine rear frame and passes into the exhaust duct and out through the ship's exhaust.

SECONDARY AIRFLOW

Secondary air is taken from the compressor ahead of the combustion stage. It is the source

Secondary air is bled from various locations on the compressor and occasionally from the combustor outer case. The air is fed internally through passages to bearing cavities and seals, and it also cools the gas generator turbine and nozzles. On some engines the air is piped externally to seals where shafts extend outside a housing, such as a reduction gear.

Bleed air is also utilized for fuel control during startup of the engine. The air pressure acts on a diaphragm or bellows and controls the fuel schedule to the engine.

The bleed air is taken from various pressure stages due to different pressure requirements at different points in the engine. For example, the front compressor bearing seal may be under a negative atmosphere, and the gas generator turbine bearing seal may be under 50 psi. Consequently, more air pressure is needed for the turbine bearing than for the compressor bearing.

Bleed air has numerous other uses. We will not attempt to describe them all as each type of engine has its own peculiarities.

Seal air is used in the gas turbine air seals (fig. 2-32) which are of two types: labyrinth/honeycomb used in the sump and turbine areas, and fishmouth used in the combustor and turbine midframe. The labyrinth/honeycomb seal combines a rotating seal having a serrated surface with a stationary seal having a honeycomb surface. The serrations cut into the honeycomb to maintain close tolerances over a large temperature range. The fishmouth seals are sheet-metal, circular, stationary, interlocking-type seals used to prevent excessive leakage of hot combustion gas from the primary airflow.

ACCESSORY DRIVES

Because the turbine and the compressor are on the same rotating shaft, a popular

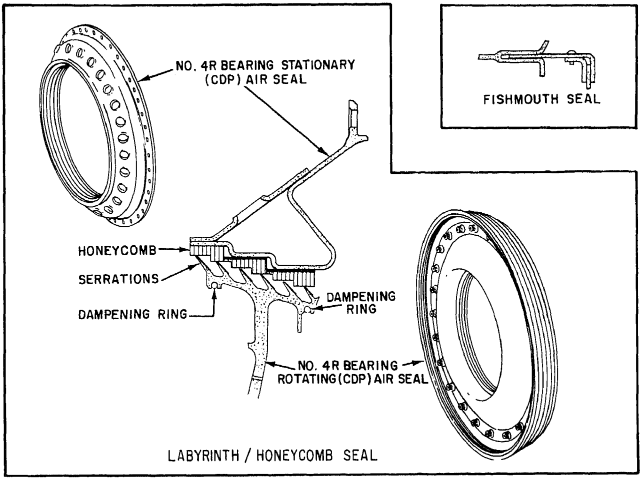

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Figure 2-32.—Typical air seals.

misconception is that the gas turbine engine has only one moving part. This is not so however. A gas turbine engine requires a starting device (which is usually a moving part), some kind of control mechanism, and power takeoffs for lube oil and fuel pumps, etc.

The accessory drive section of the gas turbine engine takes care of these various accessory functions. The primary purpose of the accessory drive section is to provide space for the mounting of the accessories required for the operation and control of the engine. The accessory drive section also serves as an oil reservoir and/or sump and houses the accessory drive gears and reduction gears.

The gear train is driven by the engine rotor through an accessory drive shaft gear coupling. The reduction gearing within the case provides suitable drive speeds for each engine accessory or component. Because the operating rpm of the rotor is so high, the accessory reduction gear ratios are relatively high. The accessory drives are supported by ball bearings assembled in the mounting bores of the accessory case.

Accessories usually provided in the accessory drive section include the fuel control, with its governing device; the high-pressure fuel oil pump or pumps; the oil sump; the oil pressure and scavenging pump or pumps; the auxiliary fuel pump; and a starter. Additional accessories, which may be included in the accessory drive section or which may be provided elsewhere, include a starting fuel pump, a hydraulic oil pump, a generator, and a tachometer. Most of these accessories are essential for the operation and control of any gas turbine engine; however, the particular combination and arrangement and location of engine-driven accessories depend on the use for which the gas turbine engine is designed.

The three common locations for the section are: on the side of the air inlet housing; under the compressor front frame; or under the compressor rear frame. One manufacturer of a generator engine, which the Navy used, had the reduction gear attached to the forward end of the compressor and the accessories mounted to the reduction gear.

CHAPTER 3

STARTING SYSTEMS

Gas turbine engines are started by turning the compressor at sufficient speed to initiate and sustain combustion. Both the compressor and the compressor turbine must be spun. In starting dual axial-flow compressor engines, the high-pressure compressor is the only one the starter needs to rotate. The starter's first requirement is to accelerate the compressor to provide sufficient airflow and pressure to support combustion in the burners.

Once fuel has been introduced and the engine has fired, the starter must continue to accelerate the compressor above the self-sustaining speed of the engine. The starter must provide enough torque to overcome rotor inertia and the friction and air loads of the engine.

Figure 3-1 shows a typical starting sequence for a gas turbine engine. When the starter has accelerated the compressor enough to establish airflow through the engine, the ignition is turned on, and then the fuel. The sequence of the starting procedure is important. There must be sufficient airflow through the engine to support combustion at the time the fuel/air mixture is ignited.

After the engine has reached its self-sustaining or self-accelerating speed, the starter can be deactivated. If the starter is cut off below the self-sustaining speed, the engine may decelerate because it doesn't have enough energy to overcome its own friction and operating losses. It may also suffer a "hung start" in which it idles at a speed so low that it is unable to accelerate enough to obtain proper operating parameters. A hung-start engine will overheat because of a lack of cooling air. The starter must therefore continue to boost engine speed well above self-sustaining speed to avoid hot or hung (false) start, or a combination of both. In a hot start, the engine lights off, but, because of a lack of adequate cooling and combustion air, the exhaust gas temperature exceeds the allowable limit for the engine.

At the proper points in the starting sequence, the starter and, usually, the ignition system will cut off. The higher the rpm before the starter cuts out, the shorter will be the total

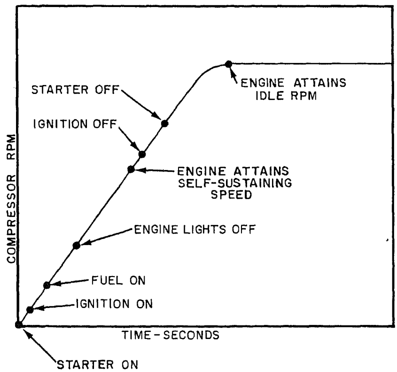

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Figure 3-1.—Typical starting sequence for a gas turbine engine.

time required for the engine to attain idle rpm, because the engine and the starter are working together.

All gas turbine starters must be able to produce sufficient torque to start the engine properly. Gas turbines must get to a certain minimum idle rate for a start to be satisfactory. Hence, the torque characteristics of an acceptable starter exceed by a good margin the amount needed to overcome friction.

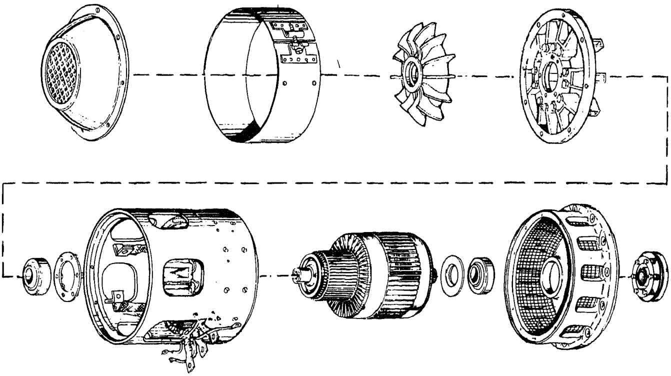
Gas turbine engines may be started by three basic types of starters and starter systems—electric, hydraulic, and pneumatic. Pneumatic (air turbine) starters are the most commonly used on all except smaller engines where electric starters are generally used. Hydraulic starters are used in some marine gas turbine installations. Combustion and cartridge-pneumatic starters are generally special application devices where a self-contained starting system may be required.

There is another starter system—the air impingement. Bleed air from another gas turbine is used directly in the high-pressure turbine assembly to rotate the gas generator. Due to the volume of air and extra engines required, the air impingement starter is used primarily in starting aircraft. Thus, we shall not discuss this system in any further detail.

ELECTRIC STARTERS

Electric starters are used on small horsepower engines that have low starting inertial loads and require high cranking speeds as compared to large engines that have a high starting torque and require low cranking speeds. A few of the older cruisers have a 750-kW emergency generator that is turbine-driven and uses an electric starter. Starting time from 0-100% rpm is an average of 40 seconds. Due to high amperage requirements the battery bank must be fully charged at all times, and the starter and all electrical connections must be maintained in excellent condition. (With a pneumatic starter, this same engine has a starting time of 15 seconds.)

The electric starter-generator (fig. 3-2) is a 28-30 VDC 500-ampere shunt-wound generator with two sets of windings. Shunt windings are



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used for the generator portion of the unit. Series windings are used for the starting portion of the unit, and compensating windings are used to reduce or prevent arcing of the brushes during operation. The starter has the following characteristics:

1. The starter-generator is one unit (one unit starts the engine and also charges its own batteries).

2. It is practical for small craft, for example, the old LCSR which had two gas turbines for propulsion.

3. It requires a cooling period if more than one attempt in succession is made to start the engine; that is, if the engine fails to start on initial start, a 15-second cooling time is required for the second and third starts. If a third attempt fails, a 30-minute cooling period is required.

OPERATION OF ELECTRIC STARTERS-GENERATORS

Close the master switch and circuit breakers; then close the start switch. The start switch contacts are magnetically held shut during the start cycle. The starter begins to turn the engine and, as speed increases and combustion occurs, the engine begins to accelerate. The starter continues to assist the engine to accelerate. At approximately 60% of rated rpm a set of relays opens and closes. The starter series unit is deenergized, the voltage regulator excites the shunt windings, and the generator starts charging the batteries and supplying power to the engine's electrical accessories.

The generator will produce current between 60% and 100% rated rpm. If the engine rpm drops below 60%, the generator is deenergized to protect the batteries and the generator itself from voltage feedback; however, the starter portion will not be energized. As engine speed again goes over 60%, the generator is reenergized.

HYDRAULIC STARTERS

Hydraulic starters were used to start the gas turbine on the first PG class gunboats that were built. Due to several types of casualties to the hydraulic starter system, the ships were modified. The hydraulic starter was removed and a small gas turbine and a pneumatic starter were installed. Due to limited use of the hydraulic system, we will only briefly describe the operation of the system. You can find more information on the basic principles of a hydraulic system in *Fluid Power* NAVTRA 16193-B.

There are several types of hydraulic starting systems in use. In most installations, the system consists of a hydraulic starting motor, a piston type-accumulator, a manually operated hydraulic pump, an engine-driven hydraulic pump, and a reservoir for the hydraulic fluid. A typical hydraulic starting system (Aeroproduct, GM), is illustrated in figure 3-3.

Hydraulic pressure is obtained in the accumulator by the manually operated hand pump or from the engine-driven pump when the engine is operating.

When the starting lever is operated, the control valve allows hydraulic oil (under pressure) from the accumulator to pass through the hydraulic starting motor, thereby cranking the engine. When the starting lever is released, spring action disengages the starting pinion and closes the control valve, stopping the flow of hydraulic oil from the accumulator. The starter is protected from the high speeds of the engine by the action of an overrunning clutch.

PNEUMATIC STARTERS

Pneumatic starters are used more than any other type for starting large gas turbine engines. These starters consist of a small air turbine (fig. 3-4) with reduction gearing and a coupling, driving through the accessory drive gear box. Air-turbine starters receive compressed air from an accumulator or the compressor of an engine already running. On ships, starting air is often

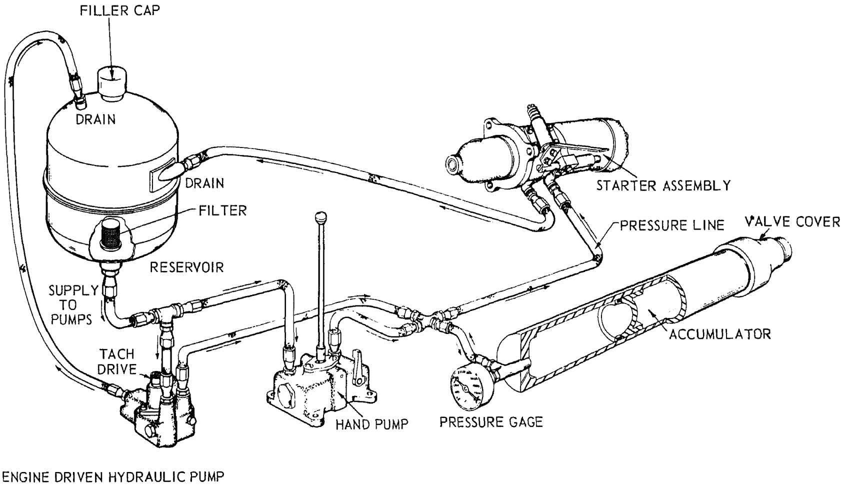

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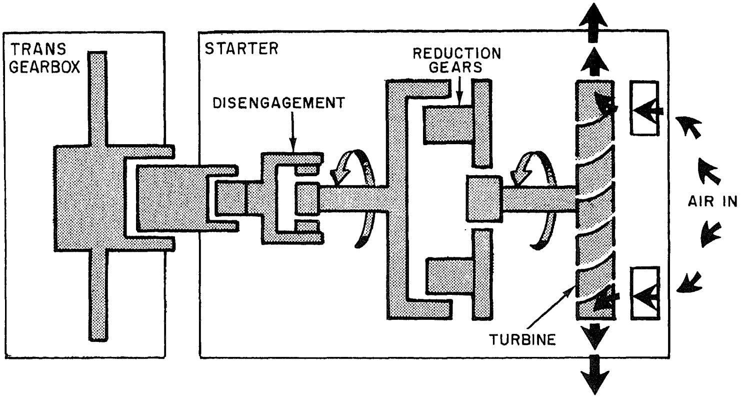
Figure 3-3.—Hydraulic starter system.

bled from an operating gas turbine generator or from the first engine started. With a pneumatic starter, it is important that an adequate volume of air is supplied at sufficient pressure. Otherwise, the starter torque will not produce consistently successful starts. When airbleed is used from another engine which is already operating, the engine being employed as a compressed air supply must be turning over fast enough to supply adequate air to the starter of the engine being started. Intercooling of air bled from an operating engine may be required.

OPERATION OF A PNEUMATIC STARTER

During a typical starting operation the pneumatic starter converts the energy of compressed air into rotational mechanical force. This force is increased in torque by a gear train and transmitted through the starter output shaft to the gas turbine engine. Compressed air is admitted through the starter inlet connection and is directed at the turbine wheel through a nozzle. The energy of the compressed air causes the turbine wheel to rotate at high speed. The air is exhausted at the exhaust connection. A planetary gear system reduces the high rotational speed, thereby increasing the torque at the starter output shaft. The engaging mechanism is a means of coupling the reduction gear system to the output shaft for engine starting. When the engine starts, the output shaft and drive shaft rotate with the engine, and the pawls of the engaging mechanism begin to ratchet. At a predetermined speed a cutout switch operates to shut off the compressed air supply. With the air supply cut off and the pawls ratcheting, the turbine wheel and reduction system coast to a stop.

Reduction of the air turbine output speed is first accomplished by the spur gear on the turbine wheel shaft driving the planetary spur gears in the gear reduction system. These



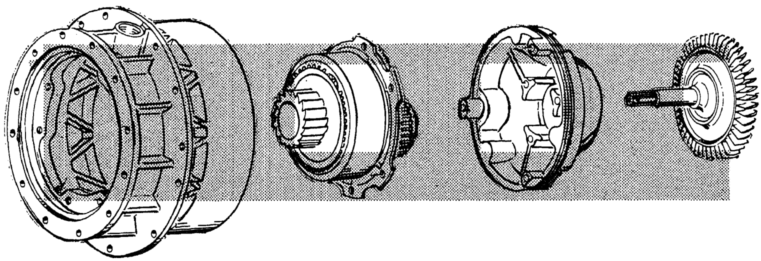


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Figure 3-4.—Pneumatic starter assembly.

planetary spur gears then transmit the rotary motion to the spur gear shafts on which they are installed. The integral spur gears on the gear shaft assemblies, in turn, transmit motion to the internal spur gear, further increasing torque. The internal spur gear turns the internal gear hub and the drive jaw which is part of the hub.

As the air turbine comes up to speed, the pawl spring assemblies in the drive shaft assembly force the drive shaft pawls to engage with the ratchet teeth of the drive jaw. This allows the drive jaw to transmit the rotational force through the drive shaft assembly to the engine. When engine light off occurs, the drive shaft assembly accelerates with the engine. Overrunning of the shaft causes the pawls to ratchet on the teeth of the drive jaw. As the speed and centrifugal force increase, the pawls function as flyweights and overcome the force of the pawl spring assemblies. This allows the

pawls to be completely withdrawn from engagement with the ratchet teeth of the drive jaw, protecting the starter from overspeeding.

WATER WASH CYCLE

A secondary use of the starting system is to motor the compressor during the water wash cycle. This cycle is automatically controlled by the operating system, and its purpose is to remove salt deposits from the compressor blades. In the cycle the turbine is motored by the starting system while freshwater is sprayed into the entrance of the compressor from a water wash spray ring located in the mouth of the turbine.

SPARK IGNITER SYSTEM

Once adequate airflow has been established through the combustion area, fuel can be injected and the spark igniters start the burning process. The spark igniters are high-voltage electrical spark producers powered from the ignition exciter circuits. (Figure 3-5.)

The ignition exciter derives its input power from the ship's service 60-Hz 115-V electrical system. Its function is to produce a high energy spark at the spark igniter in the engine. This must be accomplished with a high degree of reliability under widely varying conditions of internal pressure, humidity, temperature, and vaporization, and in spite of carbonaceous deposits on the spark igniter. To accomplish this, the capacitor discharges a spark of very high energy.

Input voltage is supplied to the exciter, being first led in through a filter which serves to block conducted noise voltage from feeding back into the electrical system. This input voltage is stepped up and applied to a full-wave rectifier. The resulting high-voltage, direct current charges a capacitor. The storage capacitor becomes charged up to a maximum of approximately 2 joules. One joule per second equals 1 watt, and the discharge, when a spark is created, takes only a few microseconds.

As the capacitor becomes fully charged, the circuit potential is enough to force current across fixed air gaps between the igniter and the

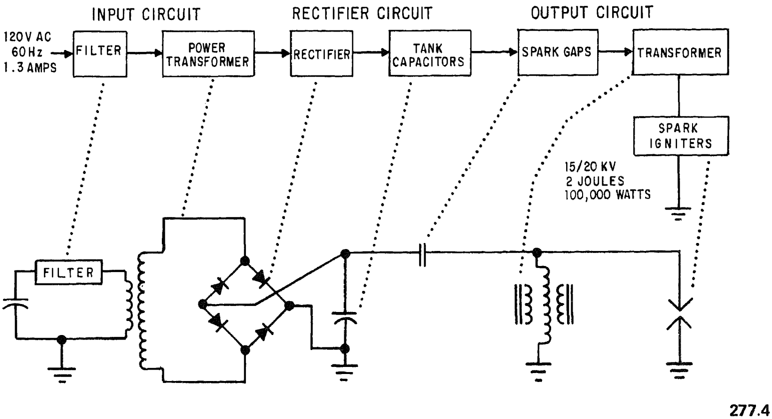
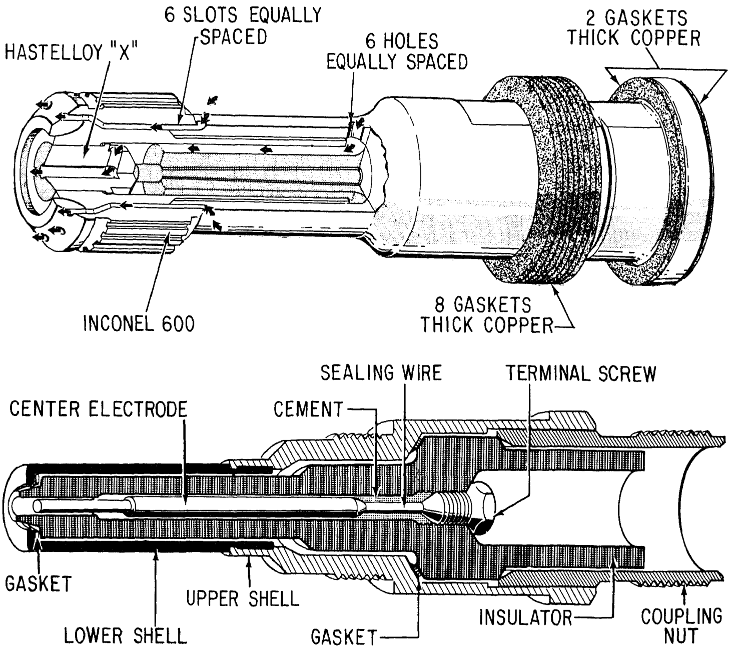


Figure 3-5.—Ignition system diagram.

tank capacitors. As the gaps are crossed, the current oscillates at high frequency between a transformer and capacitor in the discharge circuit. These oscillations ionize the air in the gap of the igniter plug, lowering the resistance in the gap. The current in the tank capacitor is now completely discharged through the oscillator circuits and the spark gap, causing a spark which represents about 100,000 watts of energy. This concentration of maximum energy in minimum time achieves an optimum spark for ignition purposes, capable of blasting carbon deposits and vaporizing globules of fuel.

Spark igniters are of several types, ranging from those resembling common automobile spark plugs to the more common annular gap types shown in figure 3-6. Since they do not operate continually, they are usually durable and reliable, requiring only occasional cleaning to remove carbon from the tip and ceramic barrel.



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CHAPTER 4

FUELS AND LUBRICANTS

Engine fuels, lubricants, and hydraulic fluids are consumable supplies. Aboard ship these items must be replaced or replenished by the proper specified types, and the supplies on hand must be correctly stored. Since several things can happen to fuels and lubricants in shipboard storage facilities, these materials must also be tested periodically to verify that they meet the required specifications.

In this chapter we shall discuss the fuel used in marine gas turbines, the lubricating oils used in the gas turbines and reduction gears, and hydraulic fluid used in various elements of the main propulsion system.

FUEL AND COMBUSTION

The modern marine gas turbine can operate on a variety of distillate fuels ranging from JP5 to Navy distillate boiler fuel. The more refined the fuel, the less it damages the areas of the engine that operate at high temperatures. Tests have indicated that turbines will last much longer when burning Navy Marine Diesel fuel than when burning Navy Distillate fuel. Navy Marine Diesel fuel has become standard for fleet use.

In general, gas turbines require a fuel that is particularly clean; otherwise, the closely fitted parts of the fuel control equipment will wear rapidly and the small passages that spray the fuel from the fuel nozzles could become clogged. The quality of the fuel must be such that it burns completely in a well-shaped flame in the combustion chamber. Its ignition qualities—autogenous ignition point and flashpoint—must permit ready starting and still make the fuel safe to handle and store.

CHARACTERISTICS AND REQUIREMENTS OF FUEL

The desirable characteristics of a marine gas turbine fuel are mostly identified in forms of what the fuel should NOT do.

1. It should not corrode the metals inside the fuel system.

2. It should not vaporize too readily since this might cause a fire hazard in transfer and storage or vapor lock in pumping and transfer system components.

3. It should not retain abrasive impurities or water too well.

4. It should not congeal or form wax deposits in the anticipated range of storage temperatures.

5. It should not form undesirable combustion products; neither those that pollute the atmosphere nor those that form deposits on or corrode turbine parts.

IMPURITIES

When the Navy accepts a delivery of fuel, the fuel meets a number of required standards including freedom from impurities. However, solid materials and water can find their way into fuel during the process of transfer and storage.

When fuel is stored in the presence of water, certain bacteria will grow in it and form a slime or jelly-like material. This slime can clog small passages and may cause some corrosion in storage containers. The bacteria can be prevented by using fuel additives or by keeping the fuel dry. The slime may be removed by filtering and centrifuging the fuel.

Solid impurities include grit and sludge from tanks and pipes and materials produced by erosion and corrosion of containers. Most of these materials will settle to the bottom of storage tanks, but they can be agitated back into the fuel by currents produced when tanks are being filled or by ship movements in heavy weather. Solids are usually removed by filters, but settling and centrifuging will also take them out.

Diesel fuel is a good solvent and may pick up solid oil-based materials such as tar or asphalt. It also may dissolve some types of sealing and caulking compounds. These materials can come out of solution when there are changes in temperature and flow and foul small passages and cause closely fitted moving parts to stick.

MAINTENANCE AND HANDLING

Maintaining the fuel tanks and transfer equipment in good condition contributes greatly to the maintenance of fuel. Little else except purification can be done once fuel of acceptable quality is taken aboard. To ensure that fuel is of acceptable quality, the following elements and factors may be tested:

1. Specific gravity in degrees API (American Petroleum Institute). Specific gravity indicates that the fuel is the specified type, since different fuels have different specific gravities. It can also detect diluting fluids such as lube oil. Another importance of specific gravity is that the energy content of a given fuel is dependent on its weight, and, since specific gravity of fuel varies with temperature, the potential energy available in a given volume of fuel must be calculated by first determining how many pounds or kilograms of fuel are in the volume. The turbine fuel control must be set to the specific gravity of the fuel being used.

2. Aniline–Gravity Constant, which predicts the heat content or potential of the fuel.

3. Smoke point, which indicates how cleanly the fuel will burn.

4. Heating value, which indicates the potential energy in each pound or gallon of fuel.

5. Distillation temperature, expressed as a range of temperatures over which the various constituents of the fuel will burn.

6. Acidity, which indicates the possible corrosive effects of the fuel.

7. Viscosity, which must be within specified limits for proper functioning of metering and vaporizing components.

8. Flashpoint, which indicates how easily the fuel will ignite on starting, and how safe it will be in storage.

9. Freezing, cloud, or waxing point, the temperature at which wax begins to separate from the fuel.

10. Pour point, which indicates the temperature at which the fuel will become highly viscous and flow too slowly for practical purposes.

11. Thermal stability, the temperature at which the fuel starts to break down to form undesirable deposits and constituents.

The primary consideration in handling fuel is to prevent leaks and spills which can present a fire or pollution hazard. The next thing is to ensure safety from any other fire or vapor explosion hazard by avoiding heat sources or sparks and by grounding against static electricity.

Once these safety considerations have been observed, you must then ensure that the fuel has the least possible exposure to water, including condensation in storage tanks. The specific tests and requirements for handling fuel are the responsibility of the ship's oil king, but it is important that you understand why special care is needed to maintain fuel quality.

THE FUEL SYSTEM

The fuel system has a number of functions. Primarily, it provides filtered and pressurized fuel for combustion. While doing this, it controls the power output of the gas generator, which in turn determines the amount of power delivered by the engine from the power turbine. Additionally, the fuel system provides pressurized fuel as a hydraulic medium to actuate the fuel controls and in the LM 2500 engine to control the angle of the variable compressor stator vanes.

Figure 4-1 shows the fuel pump assembly of the LM 2500 engine. Fuel from the ship's supply and transfer system enters the inlet at point A, and its pressure is boosted by the centrifugal pumping element B. A strainer element blocks larger impurities before the fuel enters the high-pressure fuel pump (D). From the pump it is directed through to the filter (E). A filter bypass (H) permits fuel to flow if the filter becomes clogged, and a differential pressure sensor (not shown) will alert the operator to excessive pressure drop across the filter element. Excessive pump output is vented back to the strainer inlet by the relief valve (F).

The fuel pump capacity is great enough to perform the required hydraulic functions in addition to providing combustion fuel. Excess fuel is bypassed in the fuel control and returned to the low-pressure side of the pump through the passage (G). Pressure in excess of the capability of this bypass is relieved by valve F in the pump assembly.

Filtered oil under pressure goes to the fuel control section where the fuel metering valve determines the amount of combustion fuel passed to the fuel nozzles. This amount of fuel is dictated by the following conditions:

1. Speed of the power turbine

2. Inlet pressure to the power turbine

3. Amount of power required of the power turbine (power demand)

4. Inlet air temperature to the compressor

5. Inlet air pressure to the compressor

The metering valve passes the fuel to a pressurizing valve. This valve, which will close against pressures less than 60 psig, ensures that pressure is adequate for hydraulic actuation purposes and sufficient to maintain a satisfactory fuel spray pattern in the combustors during low-speed operation.

On the LM 2500 engine, between the pressurizing valve and the nozzles are two shutdown valves in series (fig. 4-2). If either is closed, no fuel gets to the combustion chambers. When there is no electrical signal to either valve, fuel is shut off.

The fuel control unit also supplies hydraulic pressure to the stator vane actuators (fig. 4-3). Controlled pressure is applied to either the head or rod end of the actuators. The hydraulic signal is the product of a 3-dimensional cam which combines stator vane position feedback, compressor inlet temperature, and gas generator speed.

The fuel pump and fuel control (fig. 4-4) are assembled together and mounted on the transfer gearbox.

The LM 2500 engine has 30 fuel nozzles, each of which operates in a dual pressure range. Each nozzle (fig. 4-5) is encased in a shield which protects against heat and fuel leakage. The tip is encased in a shroud which directs

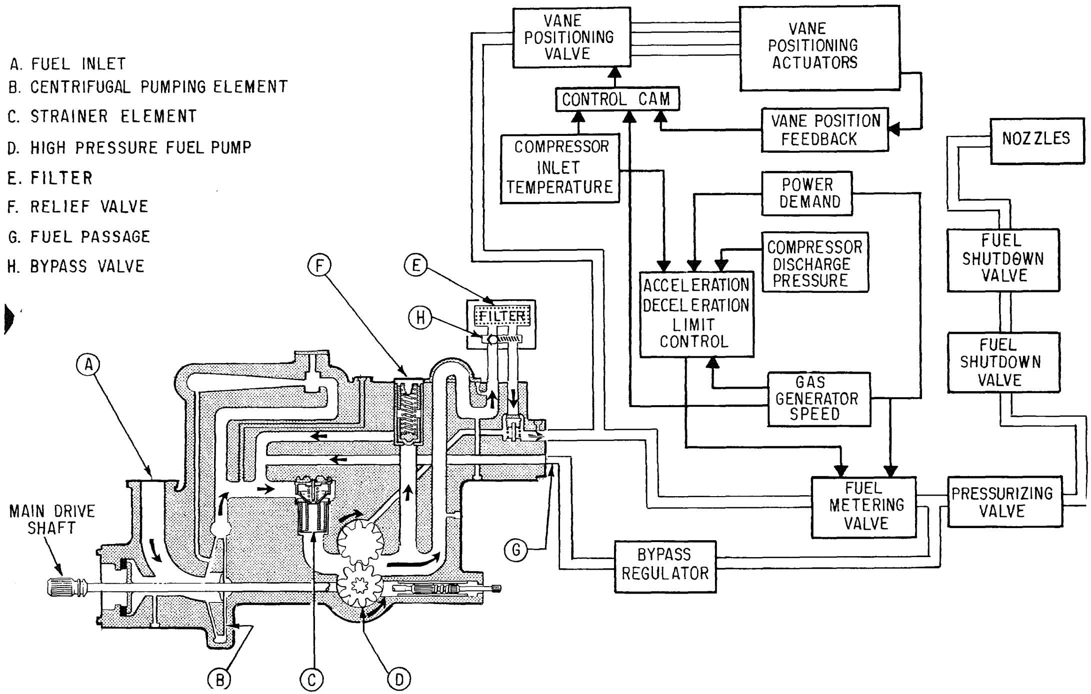

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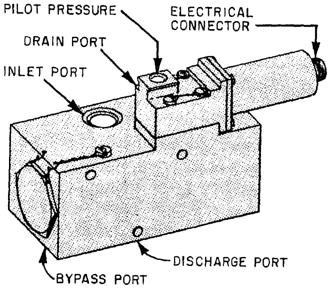
Figure 4-1.—Fuel pump and control.

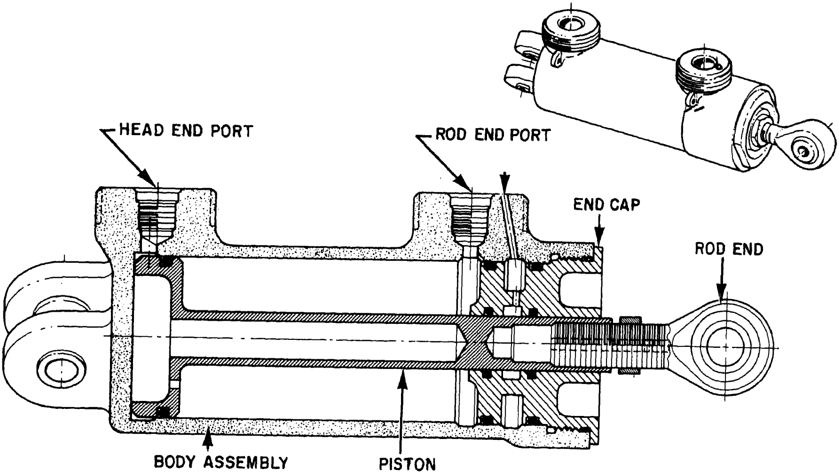


277.23
Figure 4-2.—Fuel shutdown valve.

some cooling air over the area and shields against heat. A flow divider valve directs fuel through the primary passage until fuel pressure rises over 330-350 psig, when it opens the secondary passage. A spinning of the fuel at the tip produces an atomized spray.

LUBRICANTS

Gas turbine rotors turn in ball or roller bearings or occasionally in a type of self-centering bearing called a slipper bearing. The lubricating oil coats and preserves the metal surfaces of the bearings and also carries away heat from critical areas. The oil has to work within high-pressure areas of the engine where



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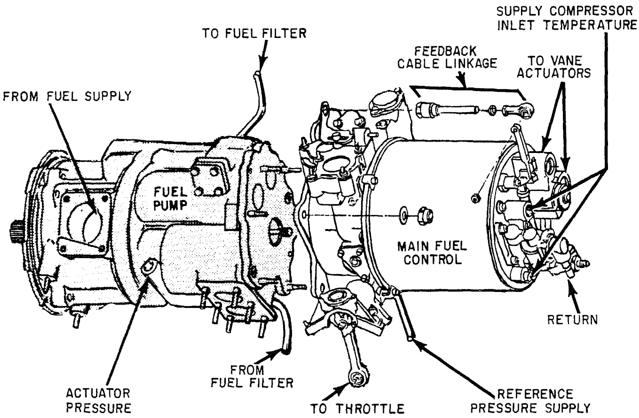

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Figure 4-4.—Fuel pump and control assembly.

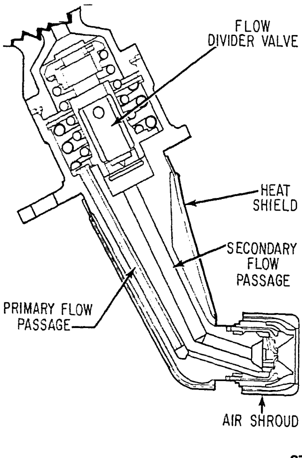

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Figure 4-5.—Fuel nozzle.

temperatures are very high and turbine cooli air passes through at high velocities. This is difficult environment for petroleum based oi so synthetic based oils are usually used. The oils are generally less viscous than those used reciprocating diesel engines.

The marine gas turbine drives through reduction gear that has lubrication requiremen and specifications similar to those associate with steam turbines. The reduction gear oil mu be viscous, to hold fluid films under the hig pressures and low speeds found in the gear trai Since reduction gear lubricants are not unique gas turbine engines, we will not discuss the further in this text.

Using the LM 2500 gas turbine as a example, we find that the basic lubricant is th synthetic oil Mil-L-23699, which is commonl used for jet aircraft engines. The basic oil reinforced with a system preservative. The pr servative may be a commercial product, Bray Co 599, or one made by mixing Lubrizol No. 85

and Dow polyglycol P-1200 with some synthetic oil. These various ingredients increase film strength and inhibit oxidation. Eight ounces of preservative should be added with each 5 gallons of lubricant when the system is being replenished.

Synthetic oils will remove paint and are toxic; therefore, avoid spills. They are dangerous in contact with your skin, and you must not breathe their vapors. Cleanup rags and other sources of synthetic oil vapor must be removed from enclosed spaces.

When the gas turbine is in operation, the oil is processed through the lube storage and conditioning assembly (fig. 4-6). Oil comes from the engine sump at temperatures up to 270° F. It is first filtered to remove solid impurities, chiefly carbon particles from the hot sections of the engine. The filtered oil is then cooled in a heat exchanger and goes into the storage tank. A deaerator inside the tank removes air which is forced into the oil from the turbine cooling system. Oil from the storage and conditioning assembly is gravity fed to the lube pump for the turbine.

The storage tank for the LM 2500 engine holds 32 gallons and should be refilled when the level is below the 24-gallon sight glass. Replenishment oil is packaged in quart and gallon cans.

Cans of synthetic oil in stock must be used within a set time limit since the oil may deteriorate on the shelf. Operating LM 2500 engines may use oil at a rate of 2 pounds per hour and still be within tolerance. By keeping records of the rate of oil consumption and rotating the stock of oil, you should be able to minimize the amount that must be thrown away.

Gages on the lube storage and conditioning assembly indicate the condition of filter elements by showing the amount of pressure drop through the filter. This drop is also monitored by the control system. A pressure drop in excess of 20 psi will cause an alarm to sound. A dual filter with a transfer and bypass valve makes it possible to change filter elements without interrupting engine operation.

To avoid a chance of water contamination, the synthetic oil is cooled by the reduction gear oil in the LM 2500 installation. Other systems use the fuel as a coolant.

CONTAMINATION

Gas turbine lubricating oil can be contaminated in the following ways:

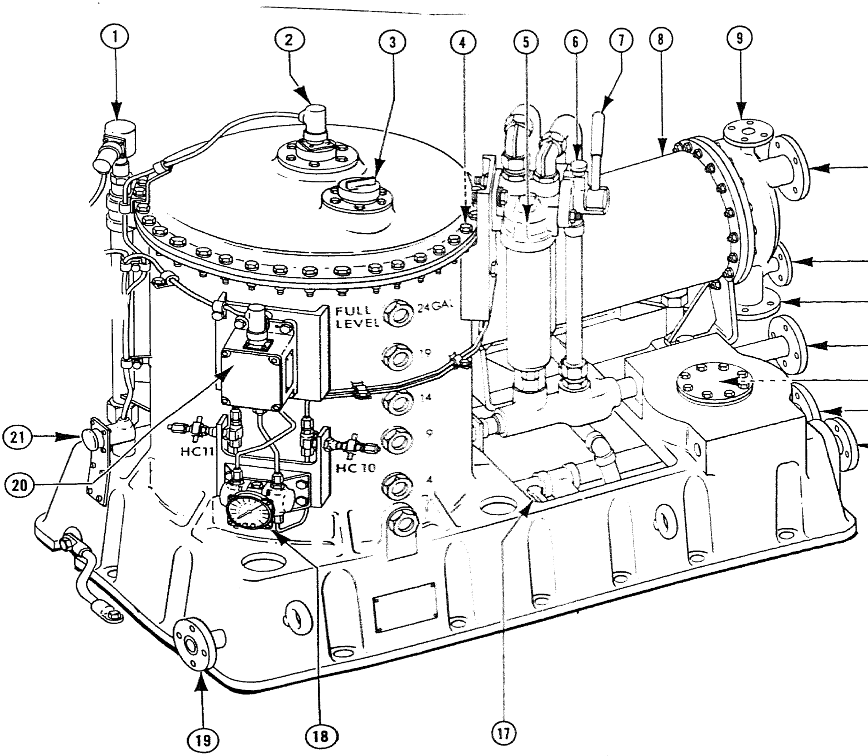
1. Water from coolers or from condensation. This is fairly rare in gas turbines.

2. Oil, either fuel oil or reduction gear oil from heat exchangers, depending on the medium used to cool the lube oil.

3. Scale, rust, and metallic products from abrasion or corrosion of metallic parts, or fragments of metal from lubricating oil containers. Rust in the oil system may be due to water in the oil, or it may be introduced externally through oil that has become contaminated from storage containers and/or servicing equipment that is not properly maintained. The presence of rust in the lube system over a period of time will eventually discolor bearing components in the lube oil pump. Ordinary rust will leave a discoloration on the bearing elements, and black iron oxides will leave a black indication. These rust particles are generally not large enough to cause pump failure, but this would depend to a large extent on the design of the pump.

4. Carbon particles and other hard carbonaceous fragments produced by oil evaporation and by sludge being baked in the hot sections of the turbine. This carbon eventually breaks off and is picked up by the pumps and circulated through the engine lubricating system. The pieces of carbon are usually not hard enough or large enough to cause failure of the pumps, but they may be large enough to clog the filter.

5. Air is the chief contaminant. It permeates the oil as a result of the spray type



LEGEND:

1. HEAT EXCHANGER OUTLET TEMP. SENSOR
2. OIL TANK LEVEL SWITCH
3. GRAVITY FILL CAP
4. HEAT EXCHANGER LUBE VENT (NOT SHOWN)
5. SCAVENGE OIL FILTER
6. FILTER SELECTOR LOCK
7. FILTER SELECTOR
8. HEAT EXCHANGER
9. HEAT EXCHANGER COOLANT VENT
10. HEAT EXCHANGER COOLANT IN
11. HEAT EXCHANGER COOLANT DRAIN
12. HEAT EXCHANGER COOLANT OUT
13. SCAVENGE OIL FROM GAS TURBINE
14. HEAT EXCHANGER LUBE DRAIN (NOT SHOW
15. LUBE OIL TO GAS TURBINE
16. OIL TANK VENT TO DRAIN
17. OIL TANK DRAIN VALVE HANDLE
18. SCAVENGE FILTER ΔP GAGE
19. OIL TANK DRAIN
20. SCAVENGE FILTER ΔP XCDR
21. ELECTRICAL CONNECTOR

HC CALIBRATION PORTS

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Figure 4-6.—Lube storage and conditioning assembly.

lubrication used in the turbine and the high pressure of the cooling air inside the turbine rotor.

6. Dirt is almost always the result of incorrect handling of the oil, such as pouring replenishment oil through dirty funnels and failure to clean filler openings and can tops before pouring oil.

7. Deteriorated oil resulting from the natural breakdown of the oil over a period of time. Synthetic oil deteriorates much more quickly than petroleum oil under storage conditions.

Most contamination is removed by filters. Air is removed by the deaerating system in the storage and conditioning assembly.

Oil samples are taken periodically and sent for spectroanalysis. As shown in figure 4-7, spectroanalysis will show the presence of specific metals and other elements in the oil. This analysis is very valuable in predicting potential casualties that may be caused by breakdown of metal parts or in detecting problems that produce metallic breakdown, such as hot spots, or rubbing of parts.

GAS TURBINE LUBRICATING SYSTEM

The lubricating system is designed to supply bearings and gears with clean lubricating oil at the desired pressures and temperatures. In some installations, the lubricating system also furnishes oil to various hydraulic systems. Heat absorbed by the lubricating oil is transferred to the cooling medium in a lube oil cooler.

The lubricating system illustrated in figure 4-8 is the dry-sump type, with a common oil supply from an externally mounted oil tank. The system includes the oil tank, the lubricating oil pressure pump, the scavenging pumps, the oil cooler, oil filters, the pressure regulating valve, and filter and cooler bypass valves.

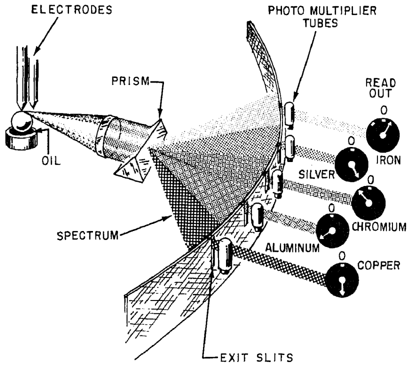

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Figure 4-7.—Spectrometric oil analysis.

All bearings and gears in the engine and accessory drives are lubricated and cooled by the lubricating system. The lubricating oil supplied to each bearing in a gas turbine engine is specifically controlled by a calibrated orifice which provides the proper flow of lube oil to the bearing at all engine speeds. This is sometimes known as a calibrated oil system. Since lubricating oil is supplied to various parts of the system under pressure, there must be some means to prevent the oil from leaking into unwanted areas, such as the compressors and turbines. This is usually accomplished by the use of carbon ring pneumatic oil seals, labryinth seals, or lip type seals which were described in chapter 2. The lubrication system provides the gas turbine bearings, gears, and splines with adequate cool oil to prevent excessive friction and heat. Oil nozzles direct the oil onto bearings, gears, and splines. Five separate scavenge elements in the lube and scavenge pump remove oil from A, B, C, and D sumps and the transfer gearbox. The scavenged oil is returned to the lube storage and conditioning assembly where it is filtered, cooled, and stored.

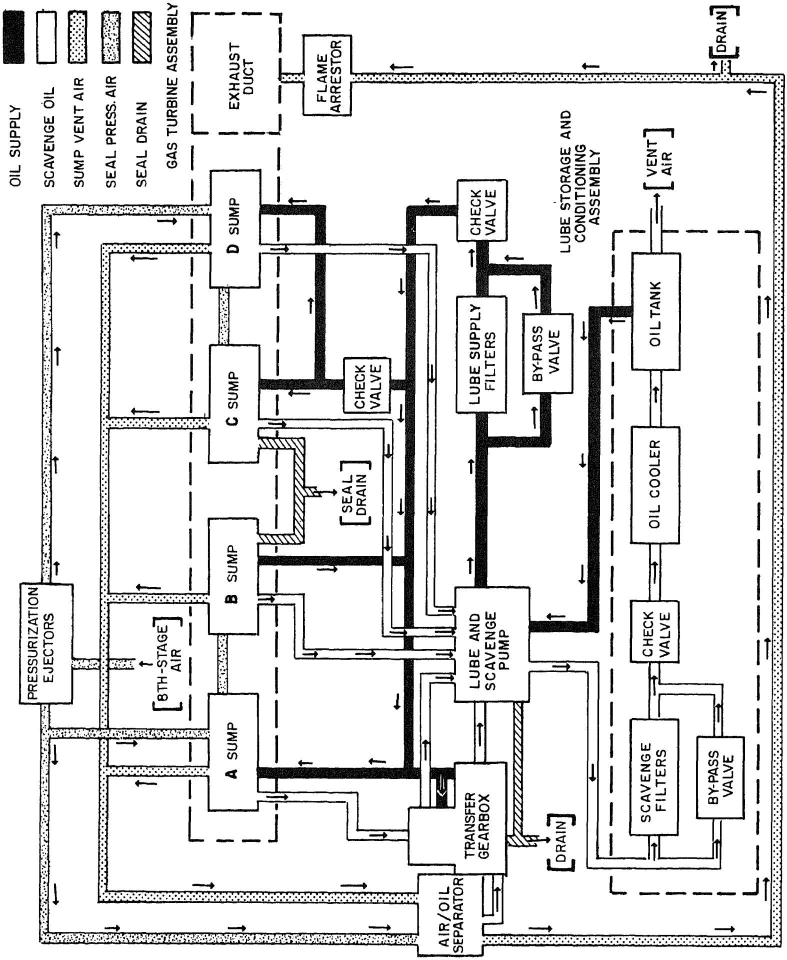

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Figure 4-8.—Lubricating system schematic.

Scavenge oil is filtered by a duplex filter mounted on the lube storage tank.

The lubrication system is divided into three subsystems identified as lube supply, lube scavenge, and sump vent.

LUBE SUPPLY SUBSYSTEM

The lube supply subsystem (fig. 4-8) consists of the following components:

1. Oil tank

2. Lube and scavenge pump supply element and cold start bypass valve

3. Lube supply duplex filter

4. Lube supply check valve

5. C and D sump supply check valve

Lube and Scavenge Pump

The lube and scavenge pump (fig. 4-9) is a positive-displacement type containing six gerotor elements. One element is used for lube supply (just described), and five are used for lube scavenging. Within the pump are inlet screens, one for each element, and a lube supply pressure limiting valve.

Lube oil from the supply tank enters the lube and scavenge pump through an inlet screen which stops particles larger than 0.030 inch. Output of the supply pump element is routed to the lube supply duplex filter (fig. 4-10). The duplex filter has a pressure relief bypass valve to allow full flow to the gas turbine if the filter element becomes clogged. From the filter the oil flows through a check valve to the inlet gearbox, the transfer gearbox, and the gas turbine sumps.

Supply Check Valves

The lube supply check valve is located on the downstream side of the lube supply filter. It will open with a maximum differential pressure of 15 psi and has a capacity of 20 gpm. The purpose of the check valve is to prevent the oil in the tank from draining into the sumps and gearbox when the gas turbine is shut down.

A check valve is located in the lube supply line to the C and D sumps to keep the lines primed while the gas turbine is shut down.

LUBE SCAVENGE SUBSYSTEM

The lube scavenge subsystem consists of the following components:

1. Lube and scavenge pump scavenge elements

2. Lube scavenge duplex filter

3. Lube scavenge check valve

4. Heat exchange (oil cooler)

The five scavenge elements of the previously described lube and scavenge pump remove oil from the B, C, and D sumps, and from two areas of the transfer gearbox.

Scavenge Oil Filter

The scavenge oil filter (fig. 4-8) is the duplex type with provisions for manual selection of either element while the gas turbine is shut down or operating.

Scavenge Check Valve

The scavenge check valve is located between the scavenge filter and the heat exchanger. It will open to a capacity of 20 gallons per minute (gpm) with a maximum differential pressure of 15 psi. This check valve prevents the oil in the scavenge lines from draining back into the sumps and the gearbox when the gas turbine is shut down.

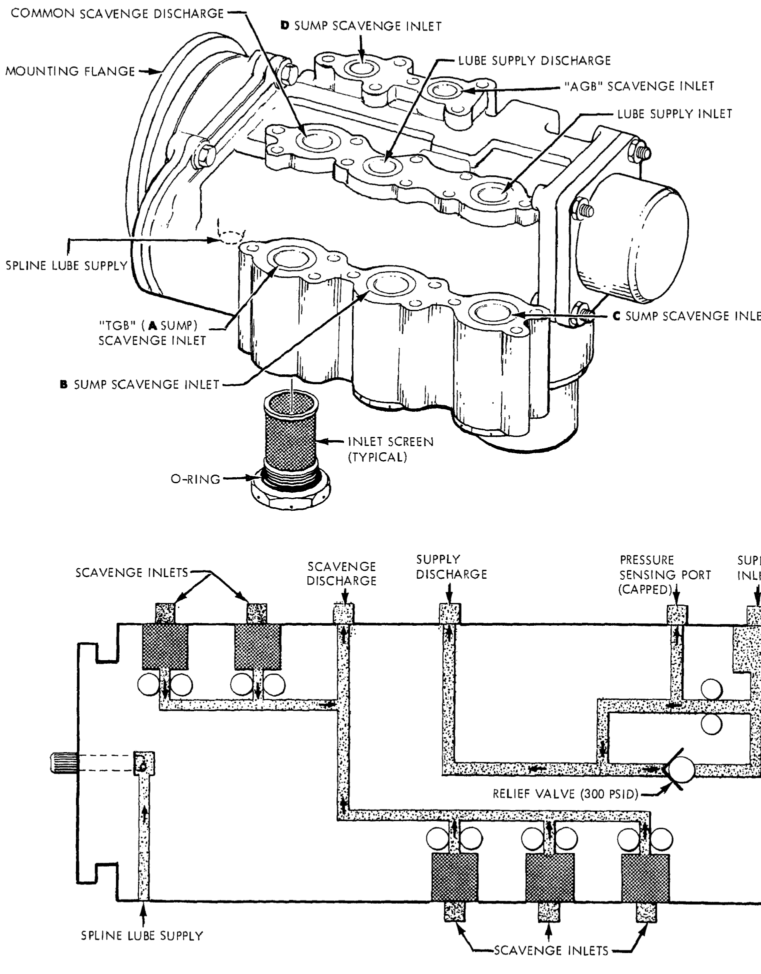

Figure 4-9.—Lube and scavenge pump.

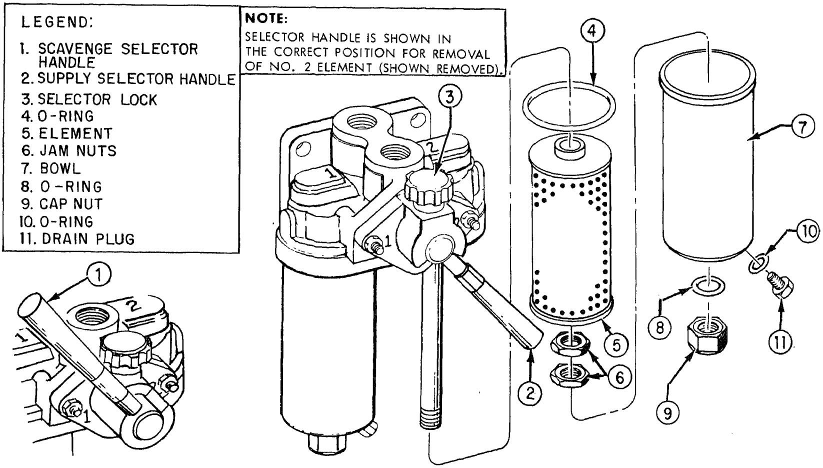

Figure 4-10.—Lube supply filter, scavenge filter.

Heat Exchanger

The heat exchanger (oil cooler), shown in figure 4-11, is a shell-tube assembly with the coolant (reduction gear oil) passing through the inside of the tubes and the turbine lube oil flowing around the outside of the tubes. Flange-type ports are used for coolant connections; threaded ports are used for oil inlet, discharge, and venting. The end domes are removed for direct access to the inside of the coolant tubes for cleaning.

OIL SEALS.—(See figure 2-30.) The oil seals were described in chapter 2. They are labyrinth/windback types used in the sump areas, and carbon seals are used in the transfer gearbox.

SUMP VENTS

The bearings drain to the lube oil scavenge pumps and are vented to a centrifugal air/oil separator, which salvages oil vapor and discharges air into the exhaust duct. Figure 2-13 shows a bearing sump vented through one of the diffuser guide vanes.

HYDRAULIC FLUIDS

In gas turbine propulsion systems hydraulics are used for various control functions. The proper fluid to be used is specified for each system. Since most control functions of the main propulsion system occur in a fairly stable or predictable temperature environment, fluids used in these systems do not need to meet many of the requirements imposed by use in weapons systems. As with other hydraulic systems, the fluids must be within the specified viscosity range, must provide lubrication, and must be chemically stable. They must also be noncorrosive, nontoxic or minimally toxic, and resist combustion.

The primary concern of the operator and maintainer of gas turbine propulsion systems is

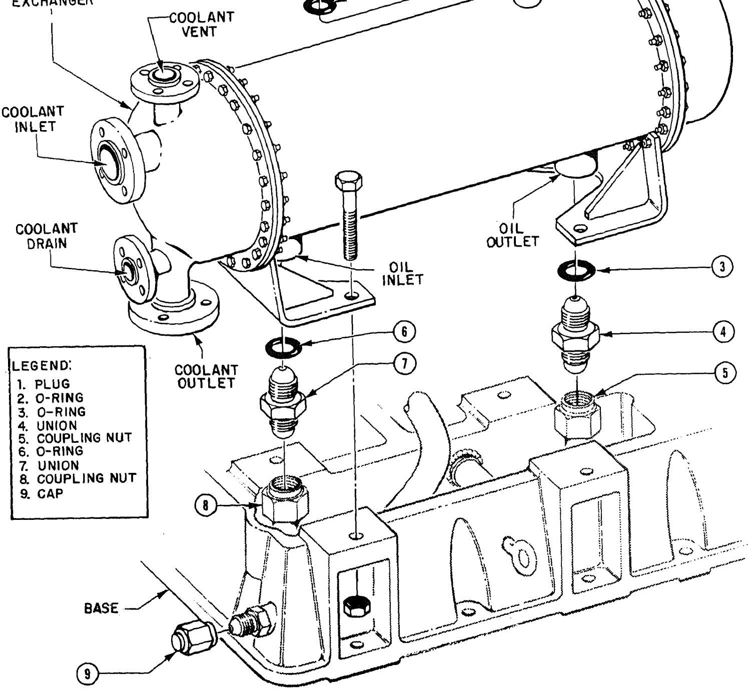

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Figure 4-11.—Heat exchanger.

an adequate and clean supply of hydraulic fluid. If foreign objects or materials get into the hydraulic system, more than changing fluid or flushing the system will be required to prevent damage to the system components.

The text *Fluid Power,* NAVPERS 16193-B is a good source of information on the care of hydraulic fluids and the general designs of hydraulic systems. The principal hydraulic systems of concern to the marine gas turbine technician are the propeller system and controls for the variable stator vanes in the compressor. The stator vanes are operated as part of the fuel system.

CHAPTER 5

AUTOMATED CENTRAL OPERATING SYSTEM

Naval engineers are constantly striving to design a more reliable engineering plant which provides quick response and requires fewer personnel to man it. With advances in engineering technology, the use of solid state devices, and the addition of logic and computer systems some of these design goals were achieved in the automated central operating systems (ACOS).

As shown in figure 5-1, ACOS centralizes the engineering plant with all controls and indicators located at one station, thereby allowing monitoring and operation by fewer watchstanders. The use of logic and computer systems reduces the chance of operator error in performing an engineering function. Automatic bell and data loggers reduce the task of hourly readings previously taken by watchstanders.

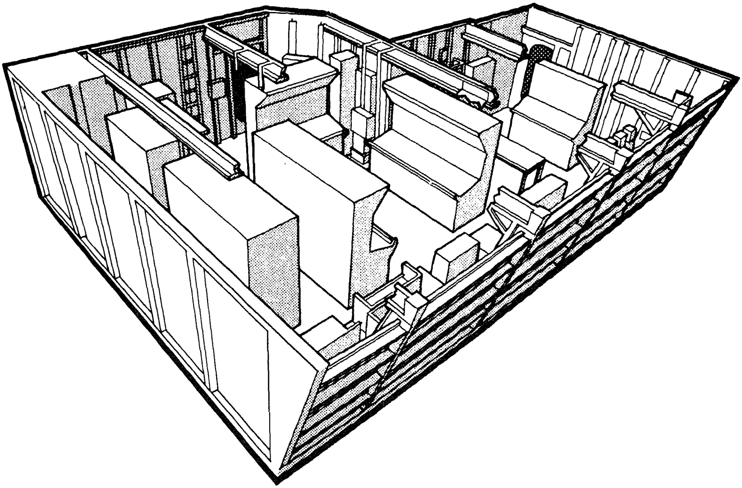

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Figure 5-1.—Typical Central Control Station (CCS).

Probably the single, most important function of ACOS is the automatic and continuous monitoring of the engineering plant conditions (parameters) and the subsequent automatic alarm if a condition exceeds a set limit or parameter.

Most new ships are being equipped with some type of ACOS. Although each ACOS has different design features, they all contain the basic concepts just discussed. For this reason this chapter will describe the ACOS that deals primarily with a gas turbine, reduction gear, and controllable reversible pitch (CRP) propeller propulsion system which is currently being installed in new construction ships. Rather than explain complex electrical diagrams and digital theory, we shall treat this system in basic terms using simplified block diagrams, so that you will have a better basic understanding of ACOS. You will find more detailed information in the manufacturers' technical manuals, *Digital Computer Basics,* NAVEDTRA 10088-A, and *Basic Electronics,* Volumes 1 and 2, NAVPERS 10087-C.

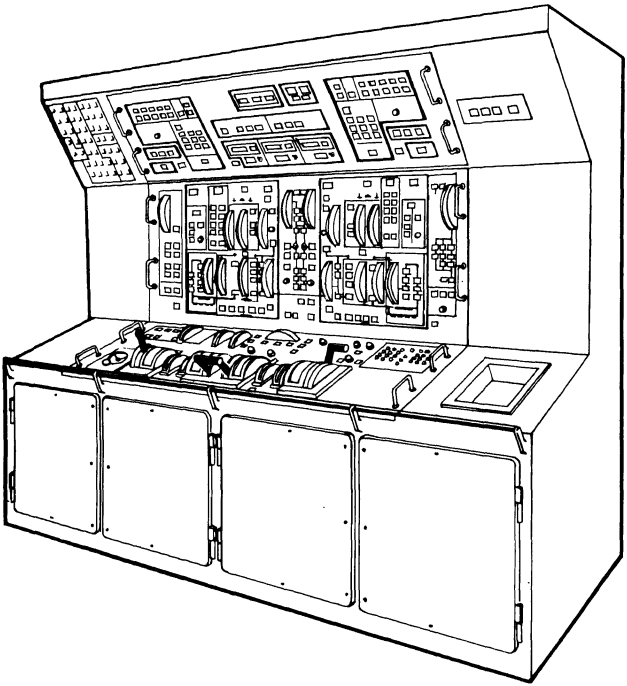

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Figure 5-2.—Propulsion Control Console (PCC).

GENERAL DESCRIPTION

ACOS provides the means for operating the ship's propulsion plant safely and efficiently. It furnishes the operators with the controls and displays required to start and stop the gas turbine engines. It also furnishes the operators with the controls necessary to change the ship's speed by means of the gas turbine speed and the pitch of the propeller. ACOS also causes the ship to move astern by setting the propeller to reverse pitch angles. These operations are performed at panels or consoles containing the necessary controls and indications for safe operation.

PROPULSION CONTROL CONSOLE

The Propulsion Control Console (PCC) (fig. 5-2) is the primary operating station for the propulsion plant and is located in the central control station. (The central control station normally has control of the entire engineering plant, including propulsion, the ship's service generators, and other auxiliary systems.) The PCC provides the operator with the necessary controls and displays for starting and stopping the gas turbine engines. Controls on the PCC allow the operator to vary the ship's forward or reverse speed within established design limitations by changing the pitch of the propeller and the speed of the propeller shaft.

The PCC provides two distinctly different methods of controlling the ship's progress through the water (fig. 5-3). The first method requires the operator to individually adjust three levers on the PCC. One lever changes the direction and amount of pitch applied at the ship's variable pitch propeller. Each of the remaining two levers controls the speed of one of the gas turbine engines.

The second and primary method of operating the ship's propulsion plant involves the use of a single PCC control lever and a special-purpose digital computer contained in the PCC. This technique for controlling the engines and the propeller pitch by means of one control and the digital computer is referred to as Single-Lever Programmed Control (fig. 5-4).

Single-Lever Programmed Control of the ship's Propulsion Plant can also be accomplished from the Ship Control Console (SCC) located on the bridge. The lever on the bridge's SCC panel can be operated only after the PCC operator in the Central Control Station relinquishes control. The PCC operator may turn over single-lever programmed control of the propulsion plant to the ship's bridge after the bridge requests it, and after controls on both consoles have been appropriately set (fig. 5-5).

LOCAL OPERATING PANEL

The Local Operating Panel (LOP), shown in figure 5-6, is the secondary operating station and normally is not manned. It is located in the machinery space near the propulsion equipment and contains the necessary controls and indicators to permit direct local (manual) control of the propulsion equipment (fig. 5-7). The direct local mode of control, although still electronic, permits operation of the equipment independently of the programmed sequencing from the computer and can be used in the event of an emergency or for control during maintenance. The LOP also provides facilities for local control of plant starting and stopping independently of the protective interlocks and logic provided by the automatic start/stop sequencer.

SHIP CONTROL CONSOLE

The Ship Control Console (SCC), shown in figure 5-8, contains the controls and indicators that permit control of the ship's speed from the bridge. This feature provides the OOD with a greater feel for the control of the ship as well as faster response to desired changes. In a twin-screw ship, steering and maneuvering of the ship may be done through this console, using the engines in addition to the rudder.

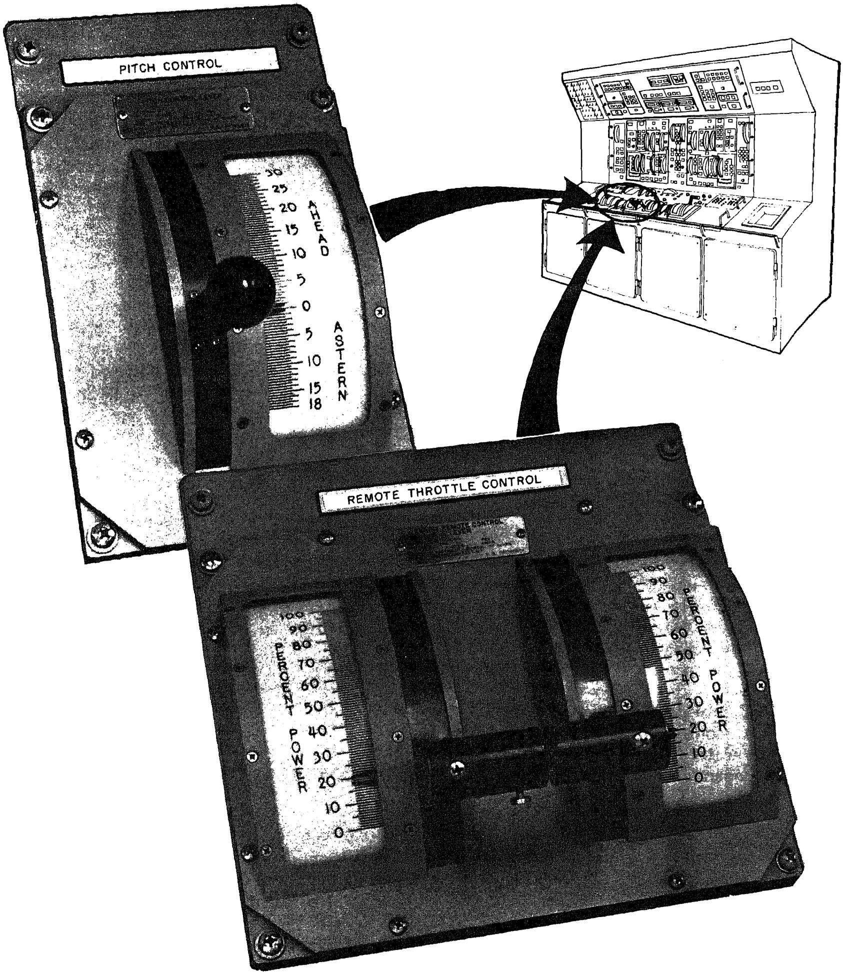

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Figure 5-3.—Manual Propulsion Plant Controls.

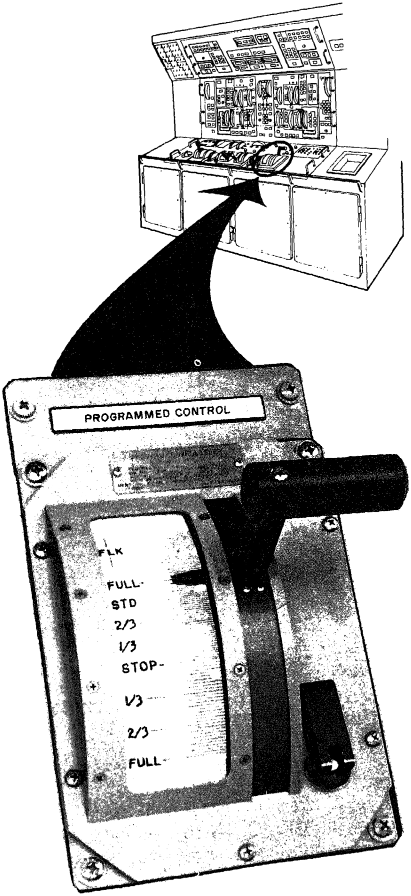

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Figure 5-4.—PCC Single-Lever Programmed Control.

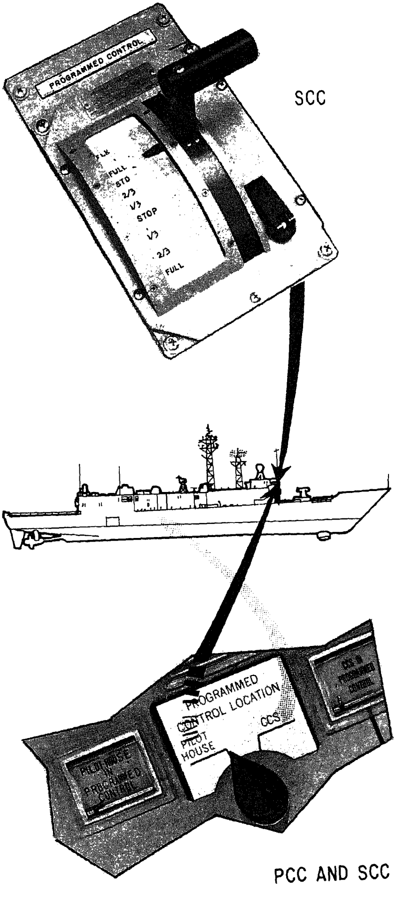

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Figure 5-5.—Bridge Control.

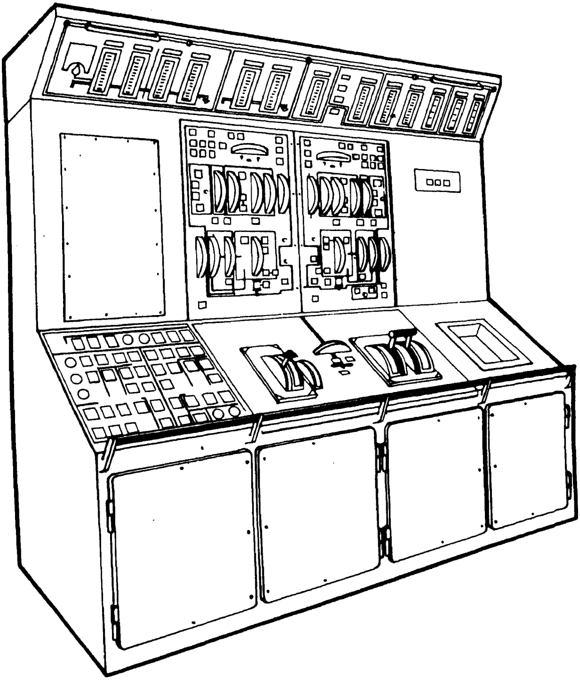

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Figure 5-6.—Local Operating Panel (LOP).

DATA LOGGER

The data logger (fig. 5-9) provides a hard copy printout of selected monitor points. The printout is initiated automatically once every hour; however, an automatic/demand control permits the operator to demand a printout of data whenever it is needed. In the event of a fault alarm, the data logger also will print out the parameter that caused the alarm. The data logger gives the time in seconds and identifies the monitored sensor (parameter range) as well

BELL LOGGER

The bell logger (fig. 5-10) provides an automatic printout each hour or whenever any of the following events occurs:

1. Propeller rpm or pitch is changed by more than 5%.
2. A bell logger printout is demanded by the PCC operator.
3. The engine order telegraph is changed.
4. The controlling station has been changed

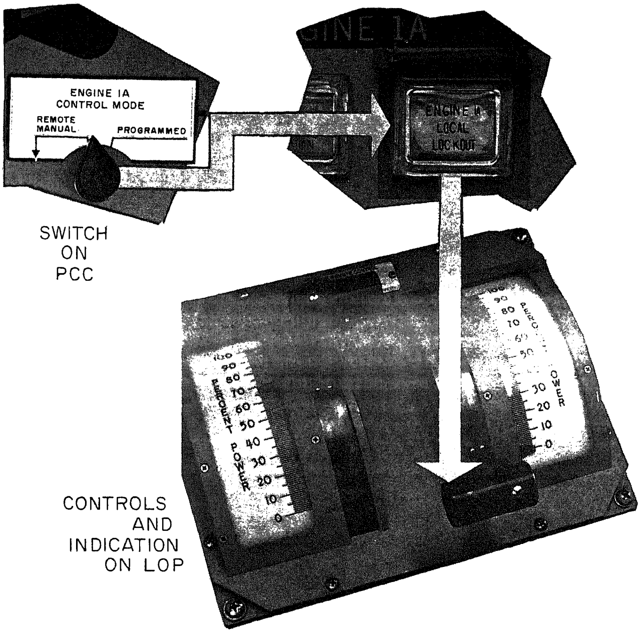

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Figure 5-7.—Engine in remote manual mode.

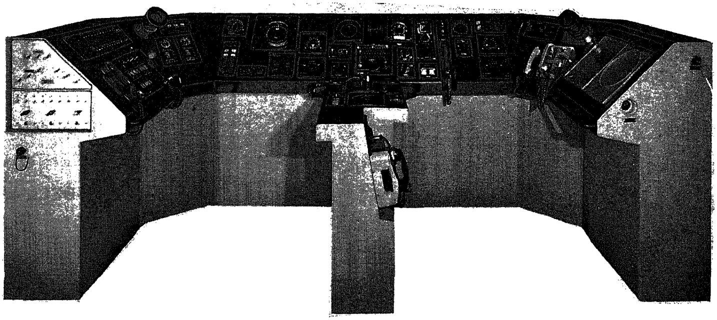

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Figure 5-8.—Ship Control Console.

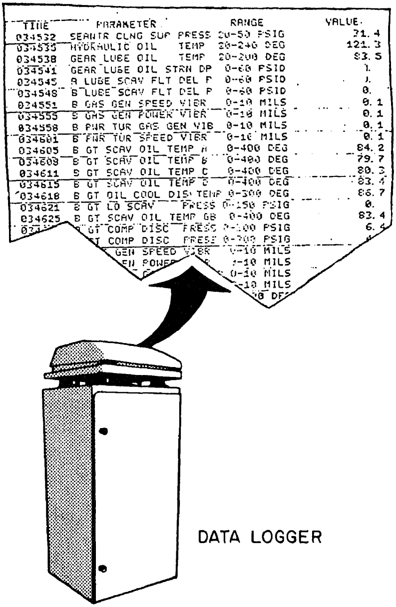

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Figure 5-9.—Data Logger and sample hard copy printout.

The bell logger prints out the following information on a 72-column preprinted page:

Time

Month

Day

Order

Station

Pitch (angle of controllable pitch propeller)

rpm

Shaft revolutions

FUNCTIONAL DESCRIPTION AND OPERATION

ACOS accomplishes several functions w can be grouped into several broad categorie follows:

1. Assists in starting and stopping propulsion plant of the ship in a manner will not create damage to equipment jeopardize the ship's tactical mis requirements.

2. Controls the speed of the engines the pitch angle of the ship's controlla reversible pitch propellers.

3. Senses, processes, and displays operator evaluation the numerous propul plant conditions or parameters.

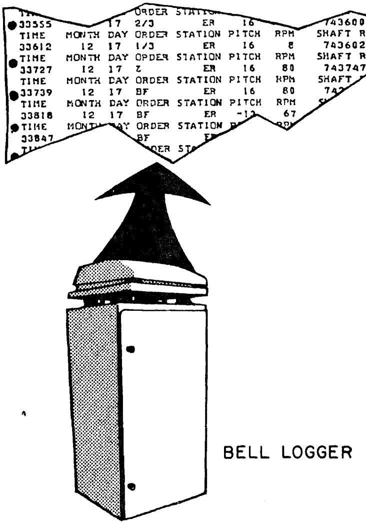

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Figure 5-10.—Bell Logger and typical hard printout.

4. Constantly monitors those parameters considered vital to the continued proper operation of the propulsion plant for an out-of-tolerance condition. If an out-of-tolerance condition is detected, visual and audible fault alarms are immediately provided to the operator.

5. Produces permanent hard copy printouts of appropriate maneuvers, conditions, and parameters for future reference and comparison.

Figure 5-11 is a simplified block diagram of the propulsion control system (PCS) portion of the ACOS showing the interfaces with the ship's propulsion plant. For simplicity the ship's electrical and auxiliary systems are not included. As you study the block diagram, you will notice that the PCS system has two primary interfaces with the propulsion system: (1) control and monitoring interfaces with the auxiliary systems and (2) control and monitoring interfaces with the gas turbine engine control modules.

Signal path A on the block diagram provides control and monitoring of the auxiliary systems from the LOP. Signal path B provides the control and monitoring of equipment operation from the PCC. Path C identifies the control station transfer signal path as well as the path

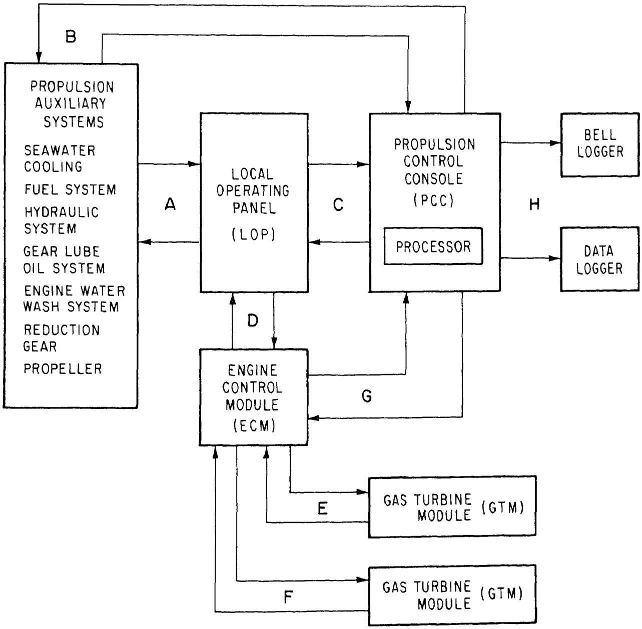

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Figure 5-11.—Propulsion Control System.

for a large number of parameters that pass through the LOP for display on the PCC. The primary path for engine control and monitoring is through the Engine Control Module (ECM) via path D. Control of fuel, ignition, starter, etc. is routed from the LOP or PCC to the ECM which connects directly to the engine modules as defined by signal paths E and F. Signal path G is the interface that provides engine start-stop control from the PCC: however, engine parameters are routed to the PCC via the LOP. Output data from the processor (the special-purpose digital computer) in the PCC to the loggers is provided via signal path H. The loggers are considered to be a one-way data path since there is no input capability from the loggers.

PARAMETER PROCESSING

Various sensors are located throughout the propulsion plant wherever pressures, temperatures, capacities, etc. are to be monitored. All these sensors produce an output in the form of an electrical signal. The signals are divided into two basic categories, discrete and analog. Discrete signals can be switch closures or relay contacts (open/closed, on/off) or any other two-state signal. Analog signals are variable values of temperature, pressure, flow, speed etc., which are calibrated in voltage or current.

Analog Signal Processing

Because of design differences, analog sensors develop different forms of signals which are in some way proportional to the units being measured. These signal differences are unacceptable to the ACOS electronic cicuitry. Therefore, the analog sensor signals are sent to electronic devices, called signal conditioners, which are located in the LOP. Signal conditioners take an input signal (which is a value proportional to the measurement but may reflect various magnitudes of voltages and current) and convert the input to an output, whose value is in the range from 0-10 VDC. After conditioning, some signals selected for continuous display on the LOP and PCC are sent to meter drivers (fig. 5-12). Meter drivers act as isolation units to segregate the meters from the electronic circuitry.

Referring to figure 5-12, you will notice all signals, including those selected for console display, are sent to an electronic device called an analog multiplexer. A multiplexer consists of several printed wire boards (PWB's) which function together to select and pass one analog signal when directed by the computer. This is accomplished by "time sampling" the inputs.

Look at figure 5-13. Assume the circle and the arrow to be a rotary switch with many inputs and one output. Also, assume the inputs all have different voltages (0-10 VDC) and the arrow is being rotated at high speed. As the arrow swings by each input, it is picked up on the arrow and sent to the output. Using this analogy and knowing that the analog signals are always available as inputs to the analog multiplexer, the computer, using a multiplex scanner, can rapidly sample (scan) all the sensor inputs. Therefore, from the analog multiplexer comes a series of analog signals, each representing an existing condition or parameter. Each signal appears in this "data stream" at least five times each second.

At this point in our discussion, all the analog signals are being conditioned and fed into a data stream for processing by the digital computer with some also being selected for continuous display on the operating consoles. You will recall that although the signals have been conditioned, they are still an analog value (0-10 VDC). To convert the signal to a digital value, we employ a device called an analog-to-digital converter (fig. 5-12). As each signal appears in the data stream, it is applied to the converter where it is changed to a digital "word" equivalent to its analog value. After all the analog signals from one multiplexer are scanned, the computer selects another to sample. This sequential scanning continues until all analog signals are sampled and "digitized" (converted to digital data). The entire process is repeated as many as 30 times per second as the computer program cycles through its routines.

As the signals are scanned and digitized, they are routed to a digital type multiplexer which is receiving various other signals (to be discussed later) for input to the computer for storage.

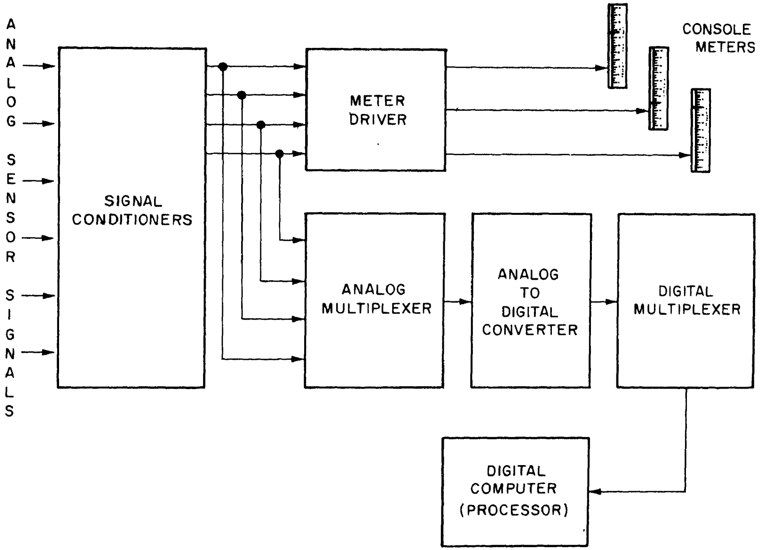

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Figure 5-12.—Block diagram of Analog Signal Processing.

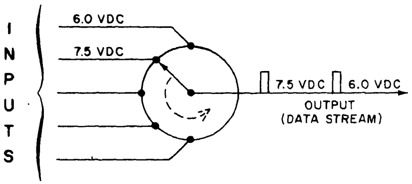

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Figure 5-13.—Electrical equivalent of Multiplexer.

Discrete Parameter Processing

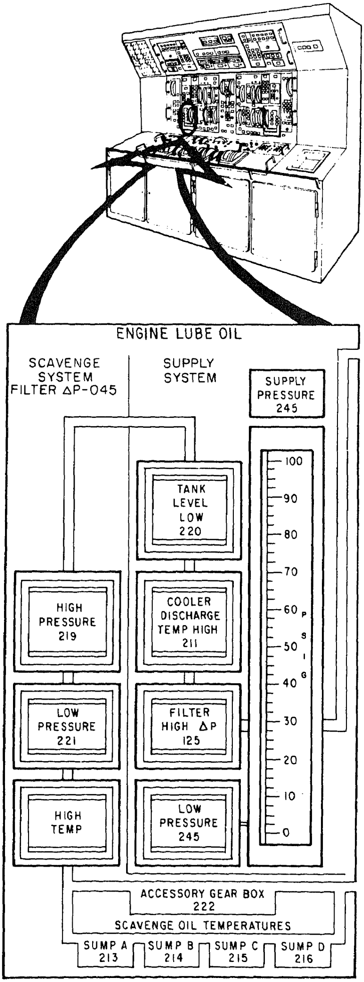
Discrete signals are grouped into two categories—vital and nonvital. Since they are

are routed directly to the previously mentioned digital multiplexer for input to the processor for storage and readout upon demand.

Vital discrete signals, because they can generate alarms, are handled differently. A discrete signal (on-off, open-close, etc.) is sent to a fault alarm detector circuit located in the LOP where it is picked up by the analog multiplex scanner and then routed to the digital multiplexer for input into the processor. Note that discrete signals are sent to the analog multiplexer for scanning only.

ALARM DETECTION

ACOS is capable of continuously monitoring many propulsion system parameters. These parameters and the existing conditions within

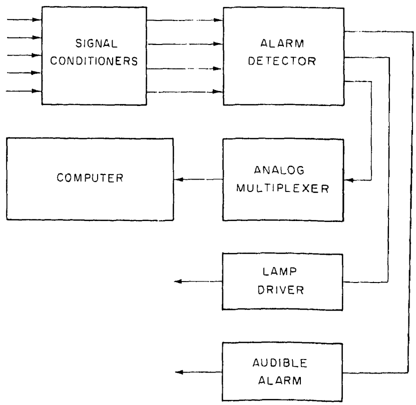


machinery, such as lube oil pressure. The alarm detection system continuously and automatically monitors the vital points and alerts the operator to the existence of a system abnormality. When a failure or out-of-limits condition is detected, audible and visual alarms (fig. 5-14) will be actuated to alert the operator.

Analog Fault Detection

Not all sensor signals are considered vital enough for alarm status and, therefore, take the signal route as previously described in analog signal processing. The parameters that are selected for fault detection take that same route and, in addition, take another path.

After the vital signal has been conditioned, it is routed to an alarm detector circuit, as shown in figure 5-15. The alarm circuit is built on a printed wire board. It triggers a signal if the input value exceeds the pre-set limits of the alarm circuit. The triggered signal is then sent to a lamp driver which operates to activate the alarm light on the operating panel. The signal



also activates the audible alarm. The pre-set limits established by the alarm circuit are also channeled back to the analog multiplexer for sampling by the processor (computer) to determine whether the alarm circuit hardware has functioned properly.

Had it not functioned correctly, the processor would automatically cause a processor-generated alarm (fig. 5-16) to operate, informing the operator of a fault alarm circuit malfunction and the data logger would print the alarm.

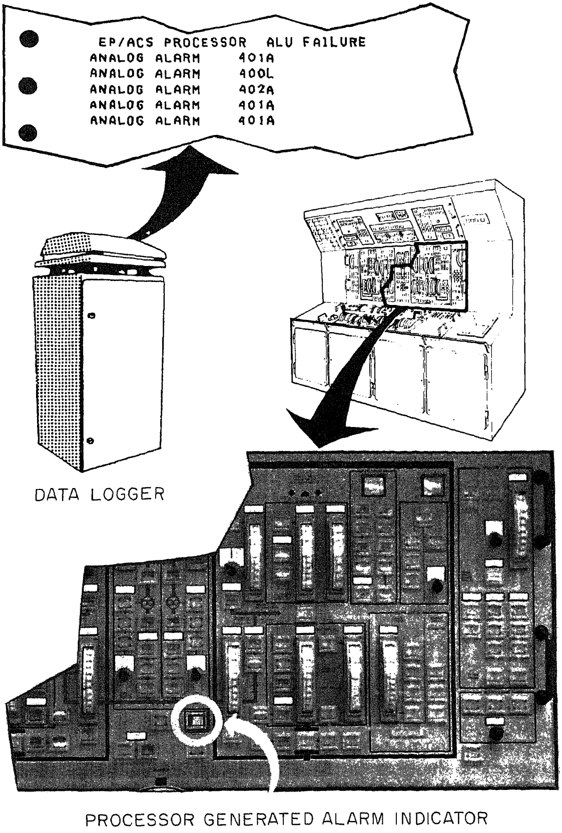


Figure 5-16.—Processor generated alarm.

Discrete Fault Detection

Discrete signals, which are selected for fault detection, are handled in very much the same manner as the analog signals. Some of the electronic circuitry is omitted because the discrete signal does not need further comparison with parameters. In the event of circuit malfunction discrete alarms are checked in a similar manner to analog signals, with the processor warning the operator of a malfunction.

The alarm system detection also incorporates special features that can be added to prevent false or misleading alarms. One provision prevents an alarm's being generated when portions of the propulsion system are shut down or are temporarily operated outside of normal limits for maintenance purposes. A second feature provides a time delay in selected sensing circuits to prevent triggering of accidental alarms during rough seas operation and in similar situations.

The operator can silence the audible alarm by depressing an "alarm acknowledge" pushbutton on the PCC. Silencing the audible portion of a fault alarm does not prevent an alarm's sounding if an abnormality is subsequently detected by another sensor, nor does it disable the visual portion of the fault alarm. When the alarm acknowledge pushbutton is depressed, the visual indicator will change from blinking on and off to a steady illumination.

PROCESSOR

The processor is a special purpose 16-bit computer that is programmed for a number of functions which include providing safe throttle and pitch commands as a function of the single lever controls while in the programmed control mode. The processor program interfaces with the ship's console loggers and the propulsion hardware, as shown in figure 5-15. The program operates on an approximate 200-millisecond cycle to perform the following functions:

1. Outputs control actions initiated through the ACOS.

2. Provide verification of the control system alarm circuitry.

3. Provide a hard copy (log) of the ship's control system operation.

4. Verify its own operational status.

5. Provide a selected display of any system condition in engineering units.

6. Provide a controlled sequence to conduct a freshwater washdown of the gas turbines.

7. Outputs engine throttle commands and propeller pitch commands.

Propulsion Control

The propulsion control function of the processor accepts an input from one of the single lever actuators. It calculates the command and control inputs both to the gas turbine throttle and to the propeller pitch hydraulic control system and produces the throttle and pitch commands. Over-torque conditions are prohibited by a limit on the rate at which shaft speed is increased at full pitch conditions and the rate shaft speed changes due to heavy sea conditions.

Engine Washdown

The processor, when directed by the operator, will automatically wash and rinse the gas turbine engines following a predetermined routine. This operation is done with the engine being spun by the starting system.

Demand Data

The demand data function responds to the request for parameter displays, which the operator makes using the thumbwheel switches (fig. 5-17), and puts the requested data on the display devices. The inputs to this function consist of the request from three sets of thumbwheel switches and data from the sensor readings which are stored in memory as described previously in parameter processing.

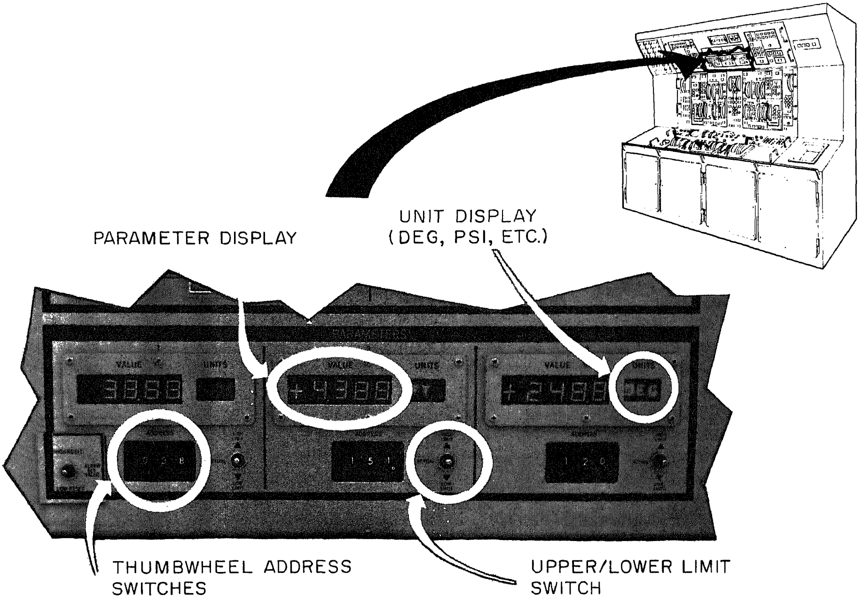


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Figure 5-17.—Demand relay display.

SUMMARY

To review the functional description of the ACOS, we refer to figure 5-18. Through the system, the operator at the propulsion control console can "see" and manipulate the entire propulsion plant. The operator is assisted by sensor scanning equipment that can check out the plant more thoroughly in a fraction of a second than an engineroom messenger could in 30 minutes. The scanning circuits are wired with information about the operating parameters of all the critical points monitored and will sound off immediately if these are exceeded. The operator's control is extended not only by remote operation of all engine controls but also by wired-in expertise from electronic components which "know" all the right steps and procedures for all normal plant operations as well as most emergency procedures.

Within ACOS there are two directions of data flow. The first is from the sensing and measuring devices on the plant equipment. The second is from the operator and the console to the engine control devices. The first, or input, flow begins as some sort of electrical signal from a sensor. These signals are "conditioned" or transformed to signals within the 0-10 VDC range. So that they can be handled by the digital computer in the system, these signals are further transformed from analog to digital form. Some of the signals are also displayed on indicators at the operating stations. Most of these indicators accept the signal in its analog form.

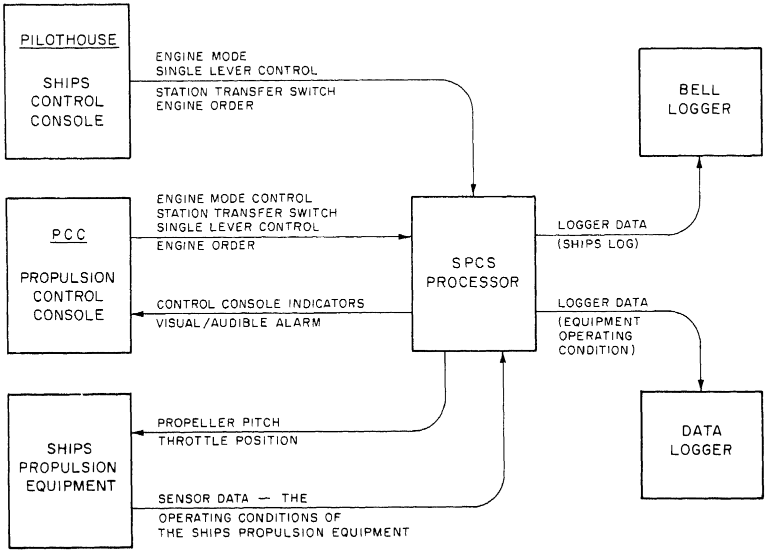

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Figure 5-18.—Interface block diagram.

The processor is a computer. To obtain sensor input it "calls the roll" of the sensors through the circuits that convert their signals to digital values. As it calls each sensor the processor compares the sensor's signal with the parameters in which it should be. If the sensor signal fits, the scan continues. All the sensors are checked in a fraction of a second through this continuous and rapid muster. Critical signals are shared with a fault detection circuit, which will alarm the operator if there are any unusual conditions. The processor also makes periodic records of selected conditions. These are typed out on the data logger. The data logger also permits the processor to give the operator detailed information of unusual or nonstandard conditions, such as alarm conditions.

Because of its importance to the operation of the ship, ACOS also checks its own operation to ensure continued reliable operation.

The control of an extensive installation of high performance engines and other machinery is a complex operation. Automatic Central Operating Systems permit a single operator to perform this operation by extending individual ability to sense and to control. As these systems prove their effectiveness and reliability, their use will increase. Before long they will be found in some form in most of the Navy's ships.

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